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This deliverable has been submitted to the European Commission but has not yet received formal approval.
As such, its contents are still subject to modifications based on the outcome of the review process.

SYMBIO
MEET YOUR SUSTAINABILITY TARGET

D4.1 Business models Economic impact assessment

(Version 01, 28/08/26)



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Deliverable description

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WORK PACKAGE: **WP4. Deployment and support industrial symbiotic approach by measuring economic, environmental and social impacts**
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Disclaimer

Artificial intelligence-based tools were used in a supportive and non-decisional manner during the preparation of this deliverable, for literature screening, structuring, language editing and consistency checks. All methodological choices, cost assumptions, interpretations, results and conclusions were developed, reviewed and validated by the authors, who retain full responsibility for the deliverable.

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Glossary of terms

1,3-PDO	1,3-Propanediol
AFEX	Ammonia Fiber Expansion
ANRI	Alchemia-nova research & innovation gemeinnützige GmbH
ANTEJA	Anteja ECG D.O.O.
B2B	Business-to-business
BABEG	Kärntner Betriebsansiedlungs- und Beteiligungsgesellschaft m.b.H.
BMC	Business Model Canvas
CAPEX	Capital Expendidure
CEPCI	Chemical Engineering Plant Cost Index
CMU	Cardiff Metropolitan University
COGS	Costo f Goods Sold
CSL	Corn Steep Liquor
FCTA	Fundación Corporación Tecnológica de Andalucía
FU	Functional Unit
GA	Grant Agreement
GHG	Greenhouse Gas
HICP	Harmonised Index of Consumer Prices
IP	Intellectual Property
IRR	Internal Rate of Return
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LGCA	Lombardy Green Chemistry Association
MCDMA	Multi-Criteria Decision-Making Analysis
MFA	Material Flow Analysis
MSP	Minimum Selling Price
NVP	Net Present Value
OPEX	Operating Expendidure
PE	Polyethylene

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PHA	Polyhydroxyalkanoates
PLA	Polylactic Acid
PTT	Polytrimethylene Terephthalate
SA	Succinic Acid
SERN	Startup Europe Regions Network
TEA	Techno-economic assessment
TRL	Technology Readiness Level
VCG.AI	Value Chain Generator.AI
WPC	Whey Protein Concentrate
WPC-80	Whey Protein Concentrate 80%

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Executive summary

Deliverable D4.1, Business Models Economic Impact Assessment, is part of WP4, “Deployment and support industrial symbiotic approach by measuring economic, environmental and social impacts”. The deliverable builds on the regional resource mapping developed in WP1, the AI-supported circular value-chain modelling carried out in WP2, and the prioritisation, MFA and multi-criteria implementation analysis completed in WP3. Its purpose is to assess the economic viability, commercial potential and long-term sustainability of the selected SYMBIO industrial symbiosis business models, with particular attention to their ability to transform regional bio-based residues and side-streams into market-relevant bio-based products.

The methodological approach combines three complementary analytical pillars: (i) a technical and commercial evaluation (Market, Competitor, Brand/Model, IP and Value-Proposition Analysis per Product); (ii) a Business Model Canvas summarising the operating model (value chain, key resources, key partners), the value model (value proposition, product system), the service model, the experience model (brand, customer relationship and engagement, channels) and the cost and revenue model; and (iii) a Life Cycle Costing exercise covering purchase and installation costs, operating costs, end-of-life costs or residual value, and the cost of externalities such as greenhouse gas (GHG) emissions, applied to the eleven regionally anchored BioLinks quantified in D3.2 (forestry residues to PHA in Andalusia and Croatia; corn residues to succinic acid in Piedmont; whey to proteins in Friuli Venezia Giulia and Wallonia; barley straw to succinic acid in Veneto and Carinthia; wheat straw to PHA in Piedmont and Slovenia; and corn steep liquor to 1,3-propanediol in Flanders/Belgium).

The expected result of D4.1 is not only a set of cost estimates, but a decision-oriented assessment of whether each symbiotic business model can plausibly progress towards deployment under realistic market, cost and regional ecosystem conditions.

Beyond its direct scope, D4.1 provides the quantitative economic and business-model foundation for the remaining WP4 activities addressing the environmental and social value layers of the Triple Layer Business Model Canvas

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1. Introduction

1.1. Task and objective

The SYMBIO project (Grant Agreement No. 101135166) supports twelve European pilot regions in six countries—Italy, Spain, Belgium, Croatia, Austria, and Slovenia—focusing on developing circular, bio-based business models that leverage industrial symbiosis and circular-by-design value chains. Its main goal is to enable European regions with highly profitable and sustainable symbiotic business models that can be easily replicated across the EU. The project employs a four-phase approach: establishing Regional Data Hubs (WP1); designing circular value chains using AI, called "BioLinks®" (WP2); creating a decision-support and monitoring framework (WP3); and evaluating the comprehensive impacts of these business models through a Triple Layer Business Model Canvas (WP4).

Work Package 4 builds directly on the outputs of WP1–WP3. WP1 (D1.1, D1.2) developed the Regional Data-Hub methodology and estimated the availability of primary and secondary biomass across twelve pilot regions. WP2 (D2.1, D2.2) identified 579 companies and 102 clusters within the pilot regions, using the VCG.AI platform to generate 47–48 priority BioLinks. These BioLinks connect regional biomass streams to twelve targeted bio-based products—such as lactic acid, glycerol, succinic acid, acetic acid, adipic acid, PLA, PHA, lysine, glutamic acid, 1,3-propanediol, furfural, and sorbitol—and to companies acting as feedstock suppliers, technology partners, and market off-takers. WP3 (D3.2) employed a Multi-Criteria Decision-Making Analysis (MCDMA) to select the top-performing BioLinks. This selection was refined through an Expert Validation Workshop, resulting in a final core set of six highly promising, replicable value chains and eleven regionally anchored BioLinks. Material flows for each were then quantified using a harmonised Material Flow Analysis (MFA), visualised as Sankey diagrams, complemented by a qualitative multi-criteria assessment of economic, environmental, and social factors.

Task 4.1, Business models economic assessment, as outlined in the Action description, involves a technical and commercial analysis to evaluate the profitability and long-term sustainability of 10 identified symbiotic business models. The assessment covers market conditions, competitors, brands and models, intellectual property, and the value proposition of these models relative to linear ones. A Business Model Canvas visualisation summarises the operating model (value chain, key resources, key partners), the value model (value proposition and product system), the service model, the experience model (brand, customer relationships, engagement, channels), and the cost-revenue structure. This economic evaluation is complemented by Life Cycle Costing (LCC), a methodology that runs alongside Task 3.1 to assess costs throughout the product's lifecycle—from production to disposal. Typically, the analysis includes costs related to industrial symbiosis models such as purchase and installation (including delivery, setup, insurance), operating costs (energy, fuel, water, parts, maintenance), end-of-life costs (decommissioning, disposal), residual value, and externalities like greenhouse gas emissions.

Within this framework, D4.1 connects the strategic prioritisation and material quantification from WP3 to the practical issue of business viability: whether each symbiotic BioLink can operate profitably, attract investment, and remain competitive in the market. While D3.1 identified the most promising value chains and D3.2 determined the potential material flow, D4.1 focuses on answering questions about the business model, its costs, expected returns, competitive landscape, and value proposition. This makes D4.1 the

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essential link between the resource- and process-focused analyses of WP1–WP3 and the comprehensive economic, environmental, and social impact assessment that WP4 aims to deliver.

1.2. Scope

The scope of this deliverable is limited to the economic dimension of the selected SYMBIO business models, building on the eleven regionally anchored BioLinks® defined and quantified in D3.2 (1) to assess their profitability potential, commercial feasibility, market context, value proposition, business model configuration and life-cycle cost implications.

The value chains within the scope of the project are listed in Table 1.

Table 1. Selected SYMBIO value chains (bio-links)

Code	Waste	Product	Region/Country
PHA1	Forestry residues	PHA	Croatia
PHA2	Forestry residues	PHA	Andalusia/Spain
PHA3	Wheat straw	PHA	Piedmont/Italy
PHA4	Wheat straw	PHA	Slovenia
SUC1	Corn residues	Succinic acid	Piedmont/Italy
SUC2	Barley straw	Succinic acid	Veneto/Italy
SUC3	Barley straw	Succinic acid	Carinthia/Austria
PRP1	Corn steep liquor	1,3-propanediol	Flanders/Belgium
PRP2	Corn steep liquor	1,3-propanediol	Brussels/Belgium
PRO1	Whey	Proteins	Friuli Venezia Giulia/Italy
PRO2	Whey	Proteins	Wallonia/ Belgium

1.2.1. LCC scope

This study adopts a cradle-to-gate scope, covering the value chain from feedstock supply through to the delivery of the bio-based product at the biorefinery gate. This boundary is consistent with established practice for LCA and LCC of bio-based intermediates and biorefinery products *(2)*, *(3)*, *(4)*. Downstream stages (finished-product manufacturing, distribution, use and end-of-life) fall outside the analysis boundary, as several of the products under study (PHA, succinic acid, 1,3-propanediol) are intermediates entering further manufacturing or formulation processes whose technologies and cost structures are not

part of this consortium's scope. The assessment is structured around six life-cycle stages, also shown in Figure 1:

A. Feedstock Supply & Logistics (Cradle): including costs related to obtaining the agricultural waste, storing it and transporting it to the hypothetical industrial facility.

B. Feedstock Pre-Treatment: including all processes needed to reduce size and chemically (or biochemically) fractionate the feedstock material.

C. Core Bio or Chemical Process: including the main unit operations and downstream processing needed to obtain the bio-based product.

D. Industrial Waste and Emissions: including all wastes generated from pre-treating or producing the final bio-based product.

E. Industrial Symbiosis Interfaces (if possible): including all exchanges of heat, energy or mass that could be generated from the pre-treatment or production of the final bio-based product.

F. End-of-System Handover (Gate): including logistics needed to deliver the bio-based product to finished product facilities.

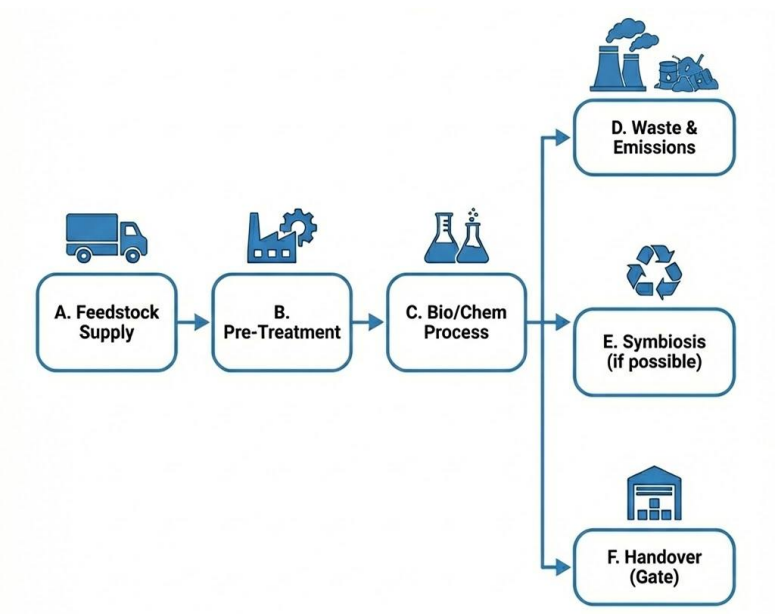

Figure 1. Life cycle stages included in the scope of the LCC.

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2. Methodology

2.1. Technical and commercial assessment

Task 4.1 involves analysing the market, competitors, brands/models, intellectual property, and the value proposition of symbiotic models compared to linear ones. These five aspects relate to the product and the technology behind it, not the region where a BioLink is located. The eleven BioLinks identified in D3.1 and measured in D3.2 actually focus on four main target products, each supported by two feedstock/region combinations for two of them. Conducting the technical and commercial evaluation once per product, rather than once per BioLink, prevents repeating identical market and competitor analyses across regions targeting the same product.

For each product, the assessment follows the same five headings:

- Market: worldwide (including EU where data exists) size, compound annual growth rate (CAGR), demand influences and limitations, plus the division between linear (fossil-based) and symbiotic (bio-based) segments of the same product market when these segments are reported separately by market intelligence sources.
- Competitors include the top linear or fossil-based incumbent(s) and the leading established bio-based producers of the same product, named explicitly to provide a clear and verifiable competitive landscape instead of a vague statement such as “many competitors exist.”
- Brands/models, named commercial product grades or brands already on the market, used as reference points for price positioning and for benchmarking the functional claims (e.g., certification, GHG-reduction percentage) that a SYMBIO-derived product would need to match or beat.
- IP: a preliminary, desk-based assessment to determine if the core conversion technology in the D3.2 Material Flow Analysis for each BioLink is proprietary, licensed, or publicly available, and to identify any indications of freedom-to-operate risks or opportunities, such as recent patent expiries, from the reviewed sources.
- Value proposition vs. the linear baseline: a four-criterion comparison table (price competitiveness, technical/functional performance, sustainability and regulatory positioning, supply security) contrasting the symbiotic, SYMBIO-relevant product with the linear baseline it is intended to displace or compete with.

2.2. Business model assessment using Business Model Canvas (BMC)

In this deliverable, the Business Model Canvas serves as a structured tool to transform the technical, commercial, and economic evidence into a clear depiction of each symbiotic business model. Rather than viewing BioLinks merely as technical value chains, the Canvas helps interpret them as market-focused circular business models, emphasising the conditions needed for economic viability, scalability, and potential replication across European regional ecosystems.

The nine blocks of the canvas, and the type of content each is populated with in this deliverable, are as follows:

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- Key Partners: the feedstock suppliers, technology/conversion partners and other external organisations the BioLink depends on.
- Product System: the principal operations the BioLink must perform, from feedstock collection and pre-treatment through conversion to product recovery.
- Key Resources: the physical, technological and human assets required, including the biorefinery/conversion infrastructure and the feedstock volumes.
- Value Propositions: the product and the benefits it offers a specific customer segment, benchmarked against the linear baseline in the market/competitor/value-proposition analysis.
- Customer Relationships: the type of relationship maintained with each customer segment (e.g., long-term off-take agreement, toll-processing arrangement, spot sales).
- Channels: how the product reaches, is sold to and is delivered to customers.
- Service Model: the distinct groups of buyers the BioLink serves.
- Cost Model: the CAPEX, feedstock, energy, labour and other operating costs quantified in the Life Cycle Costing exercise.
- Revenue Model: the income generated from the main product and from any valorised co-products or by-products, also quantified in the Life Cycle Costing exercise.

Figure 2 shows the CANVAS in its traditional nine-block format (5), with a brief description in each section. This blank template is used once per BioLink.

<table>
<tr>
<td rowspan="2">Key Partners
Feedstock suppliers, technology and conversion partners, and other external organisations the business model depends on.</td>
<td>Product System
The most important actions required to source, convert and deliver the product.</td>
<td rowspan="2">Value Propositions
The product and the bundle of benefits that create value for a specific customer segment, relative to the linear baseline.</td>
<td>Customer Relationships
The type of relationship established with each customer segment (e.g., long-term supply contract, toll-processing).</td>
<td rowspan="2">Service Model
The distinct groups of buyers the business model aims to reach and serve.</td>
</tr>
<tr>
<td>Key Resources
The physical, technological and human assets needed to create and deliver the value proposition.</td>
<td>Channels
How the value proposition reaches, is sold to and is delivered to customers.</td>
</tr>
<tr>
<td colspan="2">Cost Model
All costs incurred to operate the business model: CAPEX, feedstock, energy, labour and other OPEX.</td>
<td colspan="3">Revenue Model
The income generated from the main product and from valorised co-products/by-products.</td>
</tr>
</table>

Figure 2. The Business Model Canvas template

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2.3.Cost model structure

A shared cost-model template is used for all studies, capturing cost categories common across technologies and feedstocks while accommodating case-specific nuances, transparently referencing data sources, and enabling easy calculation. The model is maintained as a spreadsheet workbook with one sheet per value chain and shared sheets for global and regional variables (Annex 1), supported by a Python/Jupyter analysis layer that aggregates the chains, applies cost adjustment to a common reference year, and generates the diagnostic figures.

All pre-treatment and production technologies are treated as technologically and logistically mature, even where the value chain is not yet established in the region (prospective analysis). Each chain is evaluated under a single scenario, defined from prior SYMBIO results and agreed with the LCA specialists responsible for Task 4.2.

2.3.1. Functional Unit

The functional unit (FU) is one tonne of bio-based product at the plant gate. All cost contributions are expressed per tonne of product to enable comparison across chains of different scales.

2.3.2. Cost data sources and precision levels

Where possible, cost estimates are collected as intervals to improve robustness and avoid false accuracy. Cost data are classified by precision level, in order of priority (Table 3):

Table 2. Precision levels

Precision level	Definition
Level I	Costs both regionally and technologically relevant (specific to the feedstock, technology or logistics of the case).
Level II	Costs approximated or derived from similar EU regions, similar feedstocks or similar technologies.
Level III	Costs with no precise information available; derived via heuristics, non-EU sources or alternative methodologies.

2.3.3. Cost adjustment to 2026

Costs reported in different reference years are brought to a common 2026 basis using category-specific indices (6) (7) (Table 4):

Table 3. Cost categories

Cost category	Index applied	Purpose
Equipment / CAPEX	CEPCI (Chemical Engineering Plant Cost Index) (8)	Scale and bring equipment-derived costs to 2026.

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OPEX (utilities, chemicals, labour)	Eurostat HICP, per country (9)	Bring operating cost items to 2026 in the relevant national price level.

2.3.4. CAPEX estimation

Capital costs are estimated by the equipment-factored (Lang) method with the six-tenths rule for scaling. For each main unit operation, a reference purchased-equipment cost is scaled to the design size via $C = C_{ref} \times (S / S_{ref})^n$ with a default exponent n = 0.6. The summed purchased-equipment cost is multiplied by a Lang factor to obtain the fixed-capital investment (FCI), adjusted to 2026 with CEPCI, and annualised over the plant lifetime (10 years, straight-line) to yield a capital charge per tonne of product.

A single design scale is adopted per product (identical across geographical regions, to keep chains comparable), anchored to a documented commercial plant or techno-economic study (Table 5):

Table 4. Product scales

Product	Design Scale	Reference plant / Study
PHA	20000	Lignocellulosic PHB techno-economic models (19,000–30,000 t/y) (10)
1,3-propanediol	45000	DuPont Tate & Lyle / CovationBio, Loudon (initial 45,000 t/y; now 77,000 t/y) (11)
Succinic acid	10000	Reverdia Biosuccinium, Cassano Spinola (IT) and Succinity (ES), both ~10,000 t/y (12)

2.3.5. Logistics for transport cost

For all value chains involving spatially distributed agricultural or forestry residues (PHA1, PHA2, SUC1–SUC3), feedstock transport is estimated using a direct point-to-point road distance between the primary accumulation zone and the processing facility. The supply origin is identified as the centroid of the highest-density production area within the region, approximated by the nearest logistically relevant node (e.g. a market town, cooperative hub, or aggregation point); the destination is the assumed biorefinery location, selected based on industrial land availability, road network access, and proximity to the feedstock supply. For industrial co-products generated at a fixed processing plant (PRP1, PRP2, PRO1, PRO2), the supply origin is taken as the specific production facility, and a point-to-point distance to the biorefinery gate is used instead of a catchment-area model, following the same rationale applied to corn steep liquor in Searcy *et al*. (13). In all cases, a standard articulated lorry (>32 t gross, Euro VI) is assumed, with transport cost decomposed into fuel, driver labour, fixed vehicle costs and tolls, and expressed as a haulage rate per tonne-kilometre.

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2.3.6. PHA1, Forestry residues → PHA, Croatia.

Forest residue supply is drawn from the interior counties of Croatia (Karlovac, Sisak-Moslavina, Lika-Senj), which together concentrate the highest forest biomass energy potential in the country (14). Established biomass operators in Croatia collect woody biomass within a radius of approximately 65 km to minimise transport emissions; this figure is adopted as the representative one-way haul distance. The assumed

processing location is in the Zagreb metropolitan area, which offers the closest industrial infrastructure to the main forest supply zones. Road distance from the representative supply centroid to Zagreb is approximately 90 km via the A1 motorway, yielding a transport cost of 0.17 € t^{-1} km^{-1}, equivalent to 15–16 € per tonne of forest residue delivered to the plant gate.

2.3.7. PHA2, Forestry residues → Andalusia/Spain.

Supply origin is located in the Andévalo–Condado comarca (province of Huelva), the area of highest certified forest area in Andalusia, with 91,159 hectares certified under PEFC, and the established logistics hub for industrial-scale biomass supply in the region (15), (16). The processing facility is assumed to be located in the Seville metropolitan industrial corridor, accessible via the A-49 motorway. The one-way haul distance is 120 km, yielding a transport cost of 0.13-0.14 € t^{-1} km^{-1}, equivalent to 16-17 € per tonne of forest residue delivered to the plant gate.

2.3.8. SUC1, Corn residues → Succinic acid, Piedmont/Italy.

Corn stover supply is drawn from the cereal-producing plains of southern Piedmont and the adjacent Po Valley, one of Italy's most important agricultural regions, producing a wide variety of crops including wheat and corn. The representative accumulation zone is the Cuneo-Asti plain, with the assumed biorefinery located near Turin, the main industrial hub of the region. Road distance between the two nodes is approximately 97 km via the A6 motorway, yielding a transport cost of 0.36 € t^{-1} km^{-1}, equivalent to 35 € per tonne of corn stover delivered to the plant gate.

2.3.9. SUC2, Barley straw → Succinic acid, Veneto/Italy.

Barley straw supply is sourced from the cereal-growing plains of the Veneto Po Delta (Rovigo, Padova), where soft wheat and barley cultivation is concentrated in the flat, mechanised farmland south of Venice. The biorefinery is assumed to be located in the Padova–Vicenza industrial axis. Road distance from the representative field centroid to the plant gate is approximately 50–70 km along the A13 corridor, yielding a transport cost of 0.35 € t^{-1} km^{-1}, equivalent to 16 € per tonne of barley straw delivered to the plant gate.

2.3.10. SUC3, Barley straw → Succinic acid, Carinthia/Austria.

Austria cultivates barley on roughly 145,000 hectares in total (summer and winter combined), with arable land concentrated in the eastern lowlands (17); Carinthia itself is less intensively farmed, with straw supply drawn from the Klagenfurt Basin and the Drau Valley agricultural zone. The processing facility is assumed near Klagenfurt, the regional capital and logistical centre. Representative one-way haul distance is 40–60 km given the compact agricultural geography of the basin, yielding a transport cost of 0.36 € t^{-1} km^{-1}, equivalent to 15 € per tonne of barley straw delivered to the plant gate.

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2.3.11. PRP1, Corn steep liquor → 1,3-propanediol, Flanders/Belgium.

Corn steep liquor is an industrial co-product of wet milling and is therefore modelled as a point-to-point supply rather than a distributed feedstock. The nearest major wet-milling operation in the region is the Roquette facility complex in Lestrem, northern France, founded in 1933 and one of the largest starch-processing sites in Europe, located approximately 60 km from the Flemish border. Road distance from Lestrem to a representative Flanders biorefinery location (Ghent industrial zone) is approximately 90–110 km via the A25/E17, yielding a transport cost of 0.11 € t^{-1} km^{-1}, equivalent to 11 € per tonne of corn steep liquor delivered to the plant gate.

2.3.12. PRP2, Corn steep liquor → 1,3-propanediol, Brussels/Belgium.

Supply origin is the same Lestrem wet-milling hub as PRP1. The destination shifts to the Brussels industrial periphery (e.g. Anderlecht/Canal zone), increasing the road distance to approximately 120–130 km via the A1/E19. The marginal increase relative to PRP1 reflects the greater distance between the fixed supply point and the Belgian capital, yielding a transport cost of 0.11 € t^{-1} km^{-1}, equivalent to 14 € per tonne of corn steep liquor delivered to the plant gate.

2.3.13. PRO1, Whey → Proteins, Friuli Venezia Giulia/Italy.

Whey is a co-product of cheese manufacture and is therefore modelled as a point-to-point supply. Friuli Venezia Giulia hosts a modest but established dairy processing sector (18); the representative supply node is a mid-sized cheese plant in the Udine or Pordenone area. The assumed protein-extraction facility is co-located within the same dairy cluster or within the Trieste industrial port zone, giving a short intra-regional road distance of 30–60 km, via the A23 motorway, yielding a transport cost of 0.13 € t^{-1} km^{-1}, equivalent to 6 € per tonne of whey delivered to the plant gate.

2.3.14. PRO2, Whey → Proteins, Wallonia/Belgium.

Whey supply is drawn from dairy cooperatives in the Walloon agricultural heartland (Liège–Namur–Hainaut triangle), where bovine milk production and cheese making are well established. The processing facility is assumed in the Liège or Charleroi industrial zone. Road distance between the representative dairy supply node and the plant gate is approximately 40–70 km, via the E42, yielding a transport cost of 0.12 € t^{-1} km^{-1}, equivalent to 7 € per tonne of whey delivered to the plant gate.

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3. Technical and commercial assessment

3.1. Polyhydroxyalkanoates (PHA)

PHA is the target product of two SYMBIO BioLinks (forestry residues in Andalusia and Croatia; wheat straw in Piedmont and Slovenia), converted through a two-stage enzymatic hydrolysis/fermentation pathway (1).

3.1.1. Market

D3.2 itself cites a global PHA market of USD 65.4 million in 2023, forecast to reach USD 127.71 million by 2029 at an 11.8% compound annual growth rate (CAGR) (1). Mordor Intelligence, reporting by volume, estimates 58.89 kilotonnes in 2026 growing to 170.14 kilotonnes by 2031 (CAGR 23.64%), with Europe commanding 44.28% of the market in 2025 and Asia-Pacific the fastest-growing region (24.72% CAGR to 2031) (19).

The packaging and food-service segment lead end-use demand, with biomedical and agricultural applications the fastest-growing niches; regulatory pressure on single-use plastics and food-brand sustainability commitments are the principal demand drivers cited across all sources (20) (21).

3.1.2. Competitors

The linear baseline is conventional petrochemical polyethylene (PE), priced at approximately USD 1,250/tonne, against which D3.2 already benchmarks PHA's USD 4,000–15,000/tonne production-cost band (1). On the bio-based side, the PHA market is described as “moderately consolidated,” with five companies — TianAn Biologic Materials (China), Danimer Scientific (US), Kaneka Corporation (Japan), Newlight Technologies (US) and Mango Materials (US) — together holding an estimated 59.7% of global market share in 2025 (19), (21) Other named producers active in the market include CJ Biomaterials/CJ CheilJedang (South Korea), RWDC Industries (Singapore), Bluepha (China, which began commercial-scale PHA production in Jiangsu Province in 2022 and introduced new marine-biodegradable grades in 2023), Paques Biomaterials (Netherlands), Full Cycle Bioplastics (US), TerraVerdae Bioworks (Canada), Genecis Bioindustries (Canada) and Tepha (US, medical-grade PHA) (22). None of these incumbents is known to use forestry residues or cereal straw as feedstock at commercial scale; most rely on vegetable oils, sugars or, in Newlight's case, captured methane, which is a relevant point of technical differentiation for the SYMBIO route.

3.1.3. Brands/models

Commercially recognised PHA grades that can be used as external price and performance benchmarks include Nodax™ (originally developed by Procter & Gamble, commercialised by Danimer Scientific and RWDC Industries), Kaneka's PHBH biopolymer (marketed under the Kaneka Biodegradable Polymer/ “Green Planet” range), Newlight Technologies' AirCarbon®, and CJ Biomaterials' PHACT™ range (22). These brands compete primarily in rigid and flexible packaging and, increasingly, in marine-biodegradable and biomedical niches — the latter commanding a premium over commodity packaging grades (23).

3.1.4. IP position

Patent research traces the foundational science underlying today's leading PHA producers to a single 1994 patent (US 5,292,860, Shiotani and Kobayashi, assigned to Kaneka) which claims the use of *Aeromonas*

sp. bacteria for the biosynthesis of short-chain-length/medium-chain-length PHA copolymers (24) ; this patent was later shared with Procter & Gamble, whose PHA programme (using canola oil rather than Kaneka's palm oil feedstock) became the origin of today's Nodax™ technology (25) with a standard 20-year term from its early-1990s filing, this foundational biosynthesis patent is very likely already expired, meaning the core microbial science of scl-mcl-PHA production is plausibly in the public domain today. However, Danimer Scientific (26), which purchased the Nodax IP portfolio from P&G in 2007, has since built this into a large and actively maintained estate: as of its most recent public disclosures, Danimer holds or has filed more than 150 patents and pending applications in around 20 countries, covering biopolymer compositions, processes, derived products and applications, with the 23 foundational biotechnology patents expiring between 2022 and 2039 (i.e., several may already have lapsed) and the wider application-level portfolio running through 2038–2041 (27); a 2021 acquisition of Novomer additionally gave Danimer a separate, proprietary thermal-catalytic (non-fermentation) route to a related biopolymer, marketed as Rinnovo® (28). Taken together, this suggests an asymmetric freedom-to-operate picture for the SYMBIO route: the underlying fermentation biology is likely no longer exclusively controlled by any single incumbent, but the specific product compositions, blends and downstream applications (e.g., marine-biodegradable packaging formats) that a SYMBIO-derived PHA might target could still fall within Danimer's actively enforced, expanding patent estate. SYMBIO's own feedstock and pretreatment combination, enzymatic hydrolysis of forestry residues or wheat straw, optionally intensified through solid-state fermentation/solid-state enzymatic hydrolysis (SSF/SSEH), differs from the vegetable-oil feedstocks used by Kaneka and Danimer/RWDC and from the captured-methane route used by Newlight, and D3.2 itself notes that SSF/SSEH is "mostly still at the demonstration plant or pilot project stage" rather than a globally standardised, heavily patented commercial route (1).

3.1.5. Value proposition vs. the linear baseline (Polyethylene)

Table 6 summarises, on a single page, how a SYMBIO-derived PHA is expected to be positioned against conventional polyethylene once it reaches the market, drawing together the market, competitor and IP findings above into the four criteria most relevant to an off-taker's purchasing decision.

Table 5. PHA value proposition vs. polyethylene

Criterion	PHA (symbiotic)	Polyethylene (linear)
Price	USD 4,000–15,000/tonne — 3 to 12× the linear baseline (19).	≈ USD 1,250/tonne (20).
Technical/functional performance	Fully biodegradable in soil, freshwater and marine environments and in industrial/home composting; functional barrier properties still narrower than PE for some applications (19).	Superior barrier and mechanical performance; no biodegradability.
Sustainability and regulatory positioning	Directly aligned with EU single-use-plastics and packaging-sustainability legislation; growing food-brand and marine-biodegradability certification demand (19).	Increasing regulatory headwinds (EU packaging and plastics legislation).

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Supply security	Dependent on regional lignocellulosic residue mobilisation, subject to the soil-protection and competing-use constraints already documented in D3.2 (1).	Mature, global, but fossil-price-volatility-exposed supply chain.

3.2. Succinic acid

Succinic acid is the target product of two SYMBIO BioLinks (corn residues in Piedmont; barley straw in Veneto and Carinthia), converted through enzymatic hydrolysis followed by fermentation.

3.2.1. Market

D3.2 cites a global succinic acid market of USD 160.8 million in 2022, growing at approximately 6.5% per year (1). Updated 2026 market-intelligence data shows continued, and in some segments accelerating, growth: Mordor Intelligence estimates the total succinic acid market (petro- and bio-based combined) at USD 293.43 million in 2025, USD 321.5 million in 2026 and USD 507.28 million by 2031 (CAGR 9.56%, 2026–2031), with petro-based production still holding 58.82% of the market in 2025 while bio-based production is forecast to grow faster, at 11.02% CAGR over the same period; Europe held 31.64% of the total market in 2025 (29). Mordor Intelligence's dedicated bio-based succinic acid report values that segment at USD 155.68 million in 2026, rising to USD 176.26 million by 2031, with industrial polymers, chiefly polybutylene succinate (PBS) and polyurethane precursors, accounting for 42.65% of demand in 2025, and corn-derived glucose the leading feedstock at 38.60% of feedstock demand in 2025, directly relevant to the corn-residue and cereal-straw feedstocks used in the SYMBIO BioLinks (29). Other providers report figures in a comparable order of magnitude (e.g., USD 204.9 million in 2024 rising to USD 386.82 million by 2032 at a 9.12% CAGR) (30), so the market can be characterised as small but growing at a high single-digit to low double-digit CAGR, with the bio-based segment consistently reported as the faster-growing part of the total.

3.2.2. Competitors

The linear baseline is petrochemical succinic acid, produced from butane/maleic anhydride, against which D3.2 already benchmarks a bio-based production-cost floor of USD 2.28–2.70/kg, competitive mainly when crude oil trades above roughly USD 80/barrel (1). Named incumbents spanning both petro- and bio-based routes include BASF SE (Germany), Roquette Frères (France), Mitsubishi Chemical Group (Japan), Nippon Shokubai (Japan), Kawasaki Kasei Chemicals (Japan), Anhui Sunsing Chemicals (China), and Dow Chemicals (US) (30). On the specifically bio-based side, Roquette is the standout (31): it acquired and scaled the fermentation-route technology previously developed under the Reverdia joint venture (Roquette–DSM) and now markets its bio-succinic acid under the BIOSUCCINIUM® brand, which has achieved USDA Certified Biobased Product status for 100% biobased content. GC Innovation America (Myriant) acquired a bio-based succinic acid production plant in Texas in March 2025, expanding North American bio-based capacity (32) . Genomatica has separately licensed bio-based 1,4-butanediol (BDO) technology, a downstream derivative pathway relevant to succinic-acid-based value chains, to Chinese producers. In August 2026, Again acquires Genomatica (33).

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3.2.3. Brands/models

BIOSUCCINIUM® (Roquette) is currently the clearest branded, certified reference point for 100% bio-based succinic acid in the market and should be used as the primary external benchmark for both price positioning and sustainability-certification claims (31). Cosmetic-grade and industrial/technical-grade succinic acid are tracked as separate product grades by market-intelligence providers, with cosmetic grade forecast to grow fastest (10.55% CAGR, 2026–2031), which may represent a higher-value niche entry point for a SYMBIO-derived product ahead of lower-margin industrial/technical grades [29].

3.2.4. IP position

The history of the first commercial wave of dedicated bio-succinic-acid producers is directly relevant to freedom-to-operate and is well documented in the academic literature (34): BioAmber (Sarnia, Canada, using an acid-tolerant yeast strain co-developed with Cargill) filed for bankruptcy in 2018, and its plant was subsequently acquired by Taiwan-based LCY Biosciences, which restarted fermentation and reported production of about 18 kilotonnes per year from corn syrup as of 2021 (35); Myriant (Lake Providence, Louisiana, using an engineered *E. coli* strain on a sorghum feedstock) closed its plant in 2016 and the facility passed to PTTGC Innovation America, which has operated only intermittently since (32); the BASF–Corbion joint venture Succinity (Montmeló, Spain) has also stood largely idle (36) and Reverdia, the DSM–Roquette joint venture and originator of the BIOSUCCINIUM® process, was dissolved in 2019, with its Cassano d'Adda (Italy) plant and technology transferred to Roquette, while DSM, the original process developer, has stated publicly that it is willing to license the underlying technology to other interested parties (31). For a new entrant such as SYMBIO, the practical implication is favourable: the foundational fermentation-route IP from this first commercial generation is no longer concentrated in the hands of a single active, enforcing owner, but has been dispersed through bankruptcy, acquisition and explicit licensing offers, which lowers the likelihood of a blocking freedom-to-operate conflict on the core succinic-acid fermentation route itself. The remaining live commercial owner, BASF, and the current process owner, Roquette (via the former Reverdia/DSM technology), are nonetheless the two most important parties to screen for any still-active claims, together with enzyme suppliers (e.g., Novozymes, DSM) whose hydrolysis-enzyme patents may cover the specific pretreatment of corn residues and barley straw envisaged in the SYMBIO Material Flow Analysis (1).

3.2.5. Value proposition vs. the linear baseline (petrochemical succinic acid)

Table 7 sets the SYMBIO bio-based succinic acid route against the petrochemical baseline it is intended to displace, combining the pricing, technical, regulatory and supply-side findings established above.

Table 6. Succinic acid (SA) Value proposition vs. petrochemical SA

Criterion	Bio-based SA (symbiotic)	Petrochemical SA (linear)
Price	Production-cost floor ≈ USD 2.28–2.70/kg (29).	Competitive with bio-SA mainly below ≈USD 80/barrel crude oil (29).

Technical/functional performance	Chemically identical end-product; enables downstream biodegradable PBS and bio-BDO polymer chains (29).	Chemically identical; established downstream polymer/solvent chains.
Sustainability and regulatory positioning	Fermentation actively binds CO2; can approach negative net GHG emissions in integrated biorefineries; aligns with EU bioplastics/packaging policy (29).	No CO2-fixation credit; exposed to tightening EU chemicals/plastics regulation.
Supply security	Dependent on corn-residue/cereal-straw mobilisation, competing with existing animal-feed and bioenergy uses (29).	Mature global petrochemical supply chain, exposed to oil-price volatility.

3.3. Whey Protein Concentrate

Whey Protein Concentrate 80% is the target product of the whey-to-proteins BioLink in Friuli Venezia Giulia and Wallonia, produced via ultrafiltration, diafiltration, evaporation and spray drying.

Unlike PHA, succinic acid and 1,3-propanediol, WPC-80 does not displace a petrochemical product. The relevant "linear baseline" for this BioLink is therefore twofold: (i) whey treated as a low-value or discarded stream (animal feed, wastewater discharge) rather than valorised into a high-purity protein ingredient, which is the true business-as-usual counterfactual already discussed in D3.2; and (ii) plant-based protein isolates (soy, pea), which are the emerging market substitute competing for the same nutrition/supplement demand. Both are treated as "linear" comparators below for consistency with the DoA wording, even though neither is fossil-based in the way the other three products' baselines are.

3.3.1. Market

Coherent Market Insights values the global whey protein concentrate market specifically (as distinct from whey protein isolates and hydrolysates) at USD 4.36 billion in 2026, rising to USD 6.47 billion by 2033 (CAGR 5.8%) (37); within this, the WPC-35 grade is expected to hold 58.6% of the market in 2026, the organic segment 54.6%, and North America 42.8% of global share, with Asia-Pacific the fastest-growing region (11.5% share, highest growth rate) (38). Data Bridge Market Research reports a higher CAGR of 8.70% (2026–2033) for the same WPC-specific segment (39). Placed in the context of the broader whey protein category (concentrates, isolates and hydrolysates combined), Mordor Intelligence values the total whey protein market at USD 2.54 billion in 2026 rising to USD 3.50 billion by 2031 (CAGR 6.62%), with whey protein concentrate itself accounting for 58.96% of 2025 revenue, the single largest product-type segment, while whey protein isolate is the faster-growing grade (4.80% CAGR) (37). Sports nutrition and dietary supplements are consistently identified as the fastest-growing application segment across all sources, ahead of the larger but slower-growing food-and-beverage application base (37), (38), (39).

3.3.2. Competitors

The whey protein concentrate market is comparatively fragmented but dominated by large, vertically integrated dairy cooperatives and ingredient specialists. Named leaders include Fonterra Co-operative

Group (New Zealand), Glanbia plc (Ireland/UK), Arla Foods Ingredients (Denmark), Lactalis Ingredients (France), FrieslandCampina (Netherlands), Saputo Inc. (Canada), Idaho Milk Products and AMCO Proteins (both US), Hilmar Cheese Company (US), Milk Specialties Global (US), Carbery Group (Ireland) and Davisco Foods International (US) (39). Several of these, notably Arla Foods Ingredients, Lactalis Ingredients and FrieslandCampina, are headquartered in, or have major processing capacity in, the same broader European dairy region as the two SYMBIO BioLinks (Friuli Venezia Giulia, Wallonia) and are the most directly relevant competitive and potential off-take/partnership benchmarks.

3.3.3. Brands/models

Unlike the three other SYMBIO target products, whey protein concentrate is typically sold as a business-to-business functional ingredient rather than under a single dominant consumer-facing brand; ingredient-level brand families such as Arla Foods Ingredients' Lacprodan® range (40) are the closest equivalent to the "brands/models" benchmarks used for PHA, succinic acid and 1,3-propanediol above, and authors should verify current ingredient-brand portfolios directly with the identified competitors' product catalogues before finalising this subsection. Downstream, WPC-80 is incorporated into consumer sports-nutrition brands (protein powders, ready-to-drink beverages) and functional-food/bakery formulations, which is where SYMBIO-region off-takers identified in D2.2 are positioned.**¡Error! No se encuentra el origen de la referencia.**

3.3.4. IP position

Patent research confirms that membrane ultrafiltration of whey is a decades-old, long-since-public-domain technology (41): the earliest disclosed commercial process dates to Canadian Patent 966,361 (dated April 1975), with corresponding US filings such as US 4,202,909 (filed 1976) covering the separation of whey into a protein-rich retentate and a lactose-rich permeate (42), the same basic operating principle applied in the SYMBIO whey-to-proteins BioLink today. Ultrafiltration became the first membrane application in dairy processing in the 1970s and has been in mainstream commercial use ever since. Consequently, freedom-to-operate risk on the core separation principle (ultrafiltration → diafiltration → evaporation → spray drying) is assessed as low. Modern equipment suppliers such as GEA and Tetra Pak continue to patent specific engineering refinements — for example, GEA has disclosed a patent-pending microfiltration process for improving whey protein isolate yield and operating efficiency (43), and Tetra Pak markets pre-engineered, trademarked systems such as the Tetra Pak® UF system P ((44), but these cover discrete equipment or process optimisations rather than the underlying separation science, and can typically be avoided or licensed through standard commercial equipment-supply contracts rather than posing a project-blocking IP risk. Any meaningful differentiation available to a SYMBIO-derived WPC-80 product is therefore far more likely to come from regional provenance and sustainability branding.

3.3.5. Value proposition vs. the linear baseline

Because whey protein concentrate does not directly displace a petrochemical product, Table 8 benchmarks the SYMBIO whey-valorisation route against its true business-as-usual counterfactual (whey as an under-valorised or discharged stream) and against the plant-based protein isolates that increasingly compete for the same nutrition demand.

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Table 7. Whey protein concentrate value proposition

Criterion	WPC-80 from valorised whey (symbiotic)	Whey as low-value stream / plant-based protein isolate (linear comparators)
Price	Cost driven mainly by logistics (raw whey ≈94% water) and spray-drying energy, not by technology risk (37).	Discharging whey as wastewater carries a rising compliance cost under EU environmental legislation (37);plant-based isolates are price-competitive and improving in functional performance.
Technical/functional performance	High-quality complete protein, favourable essential amino-acid profile, high digestibility (37).	Plant-based isolates continue to close the functional/taste gap with animal proteins.
Sustainability and regulatory positioning	Valorises an existing dairy by-product, avoiding high-BOD wastewater discharge; supports circular dairy-sector positioning (37).	Discharge/under-utilisation is increasingly restricted; plant-based proteins carry their own separate sustainability narrative and growing market share.
Supply security	Whey supply is stable and tied to established regional cheese production, though logistics-constrained in mountainous catchment areas (37).	Global protein supply is ample; the competitive threat is demand-side substitution, not feedstock scarcity.

3.4. Corn steep liquor to 1,3-propanediol

1,3-Propanediol is the target product of the corn-steep-liquor-plus-glycerol BioLink in Flanders/Belgium, produced through microbial fermentation.

3.4.1. Market

D3.2 cites a global 1,3-PDO market value of USD 789.17 million in 2023 (1). Mordor Intelligence's more recent estimate is considerably lower in absolute terms, USD 435.12 million in 2026, rising to USD 620.61 million by 2031 (CAGR 7.36%), while noting that bio-based PDO already held 59.78% of the market in 2025 and is growing faster than the petrochemical route, at 8.93% CAGR through 2031; engineering plastics is the leading end-use segment (49.78% share in 2025), with textile dyeing and finishing the fastest-growing application (8.92% CAGR) (45). Other providers report substantially higher figures (e.g., USD 1,043.58 million in 2026 rising to USD 2,073.74 million by 2032 at an 11.60% CAGR (46), underscoring the same cross-provider methodology variance already flagged for PHA.

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3.4.2. Competitors

The market is dominated by DuPont Tate & Lyle Bio Products, a joint venture that pioneered the first commercial-scale bio-PDO plant (Loudon, Tennessee, 2006) using a proprietary corn-glucose fermentation process, and which now also operates the world's largest bio-PDO facility (≈ 60,000 tonnes/year, Louisiana), with further capacity expansions announced [40]. In Europe, METabolic Explorer (France) is the most relevant competitor: it holds licensing agreements with S.K. Chemicals and has partnered with DSM's Metex NØØVISTA to commercialise bio-PDO at a 5,000-tonne/year facility in Carling Saint-Avold, France, geographically and strategically the closest named competitor to the SYMBIO Flanders/Belgium BioLink. On the petrochemical side, Shell Chemicals and Chinese producers (Zhangjiagang Glory Biomaterial, Zouping Mingxing Chemical, Haihang Industry) supply cost-competitive, primarily petrochemical-route PDO to commodity segments.

3.4.3. Brands/models

DuPont Tate & Lyle markets two clearly differentiated grades that should be used as direct external benchmarks: Susterra® propanediol (47), positioned for industrial/performance applications (polyurethanes, resins, heat-transfer fluids) and reported to deliver a 61% greenhouse-gas reduction versus the petrochemical route, and Zemea® propanediol, positioned for cosmetics and personal-care formulations (48). In 2023 the company also launched Purabloc 2000, a high-purity renewable grade aimed at the more stringent end of the cosmetics specification range, signalling a strategic move toward higher-margin specialty segments (46).

3.4.4. IP position

DuPont's foundational bio-PDO technology was developed in collaboration with Genencor and Tate & Lyle and centres on an engineered *Escherichia coli K12* strain able to ferment glucose directly to 1,3-propanediol, first disclosed in patents such as US 5,686,276 (49) and subsequently extended through a family of process and purification patents, including US 6,514,733 (high-titre production using *Klebsiella pneumoniae* dha regulon genes) (50) and US 7,745,184 (further strain engineering) (51). Patent-register research confirms that this foundational estate is now ageing out of protection: US 8,183,417 B2, DuPont's key patent covering the purification of biologically produced 1,3-propanediol from fermentation broth, carries a confirmed/anticipated expiration date of 5 May 2024 (52). USPTO assignment records also show recent corporate restructuring of the joint venture, with underlying patent assets reassigned toward an entity named COVAPDO LLC in 2025, consistent with public reporting that DuPont Tate & Lyle Bio Products now operates under the name CovationBio PDO while continuing to sell under the Susterra® and Zemea® brands (48). This is a genuinely favourable freedom-to-operate signal for new entrants on the glucose-fermentation route specifically. It is, however, only partly relevant to the SYMBIO process: SYMBIO's route co-ferments corn steep liquor with crude glycerol rather than fermenting glucose alone, which is technically closer to the glycerol-based fermentation route separately patented by METabolic Explorer (using a recombinant *Clostridium butyricum* strain, a different organism and substrate logic from DuPont's *E. coli*/glucose process) (53).

3.4.5. Value proposition vs. the linear baseline (petrochemical 1,3-PDO)

Table 9 brings together the narrowing bio-premium, the documented GHG performance of the leading bio-based grade, and the CSL supply-security advantage identified above to benchmark the SYMBIO route against petrochemical 1,3-PDO.

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Table 8. Bio-based 1,3-Propanediol (PDO) vs. petrochemical 1,3-PDO

Criterion	Bio-based 1,3-PDO from CSL + glycerol (symbiotic)	Petrochemical 1,3-PDO (linear)
Price	Green premium over petrochemical PDO has narrowed from ≈25% (2023) to ≈15% (late 2025) and is expected to keep compressing [38]; CSL offers a documented ≈one-fifth cost reduction versus refined nitrogen sources such as yeast extract (45).	Mature, large-scale petrochemical production (acrolein/ethylene-oxide routes); cost advantage eroding as the bio-premium narrows
Technical/functional performance	Susterra®-grade bio-PDO already matches petrochemical PDO performance in polyurethane and PTT-polymer applications (45).	Established performance baseline across all major end-use segments
Sustainability and regulatory positioning	Up to 61% GHG reduction reported for leading bio-PDO grades; aligns with EU decarbonisation and renewable-content policy (45).	Exposed to tightening EU chemicals and decarbonisation regulation
Supply security	CSL is a steady, year-round by-product of corn wet-milling (unlike seasonal agricultural residues used elsewhere in the SYMBIO portfolio), though it competes with the established livestock-feed market for the same stream (45).	Exposed to crude-oil/propylene price volatility

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4. Business Model Canvas

To illustrate the practical application of the nine-block structure introduced in the Methodology chapter, this section provides a comprehensive narrative of one BioLink: the conversion of Corn Steep Liquor to 1,3-Propanediol in Flanders.

The Business Model Canvas (BMC) developed for Flanders focuses on the valorisation of Corn Steep Liquor (CSL), an industrial side-stream generated during corn wet milling processes, into bio-based 1,3-Propanediol (1,3-PDO) through industrial biotechnology processes. The proposed business model follows the principles of circular bioeconomy and industrial symbiosis by transforming an underutilised by-product into a high-value platform chemical with multiple industrial applications.

The value chain is based on integrating different industrial actors within the Flemish bioeconomy ecosystem. Flanders offers particularly favourable conditions for implementing this business model due to its strong industrial base, well-established biotechnology sector, advanced research infrastructure, and active industrial symbiosis networks. The region hosts a dense network of companies operating in the starch, chemical, plastics, and biotechnology sectors, creating a suitable environment for establishing circular and bio-based value chains.

A key component of the business model is establishing long-term partnerships among the different stakeholders involved in the value chain. Feedstock suppliers, mainly corn wet milling and starch processing companies, provide a continuous supply of Corn Steep Liquor. These actors are complemented by industrial biotechnology companies responsible for the fermentation and downstream processing steps required for the production of 1,3-PDO. Research and innovation organisations, including universities, technology centres and pilot facilities, support process optimisation, scale-up activities and technology development. In particular, the presence of shared pilot and demonstration infrastructures such as the Bio Base Europe Pilot Plant significantly reduces technological and investment risks associated with scale-up.

The business model further relies on industrial symbiosis facilitators, innovation clusters and regional authorities that support collaboration among stakeholders, facilitate knowledge exchange and provide access to funding opportunities. Logistics providers and specialised equipment suppliers also play a crucial role by ensuring efficient feedstock transport, storage and processing operations. Finally, downstream industrial users, such as polymer manufacturers, chemical companies, textile producers and cosmetics manufacturers, represent essential partners and market off-takers.

The main activities associated with the business model encompass the entire feedstock-to-product value chain. These include the collection, storage and logistics management of Corn Steep Liquor, feedstock pre-treatment and conditioning, microbial fermentation processes, downstream purification and quality control of the final product. Additional activities focus on process optimisation to improve productivity and economic competitiveness. Since the business model is based on industrial symbiosis principles, coordination and governance activities are particularly important to ensure stable feedstock supply, long-term contractual arrangements and effective collaboration among the participating actors.

Sustainability-related activities constitute another important component of the business model. Life Cycle Assessment (LCA), techno-economic assessments, Material Flow Analysis (MFA) and carbon footprint evaluations are required to quantify environmental benefits, assess economic feasibility and support

decision-making processes. Furthermore, sustainability monitoring and reporting activities aligned with European sustainability reporting requirements contribute to increasing transparency and market acceptance of bio-based products.

The successful implementation of the proposed business model depends on several key resources. Continuous access to Corn Steep Liquor is fundamental to guarantee production stability and economic viability. Equally important are the existing industrial biotechnology infrastructures, pilot facilities and highly skilled workforce available in Flanders. The regional innovation ecosystem, characterised by strong collaboration among industry, academia and public authorities, represents an additional strategic asset. Intellectual property related to microbial strains, fermentation technologies and downstream processing methods also constitutes an essential resource that may provide competitive advantages.

The core value proposition of the business model is the production of renewable and bio-based 1,3-Propanediol from an industrial side-stream that would otherwise have limited value. By converting Corn Steep Liquor into a high-value platform chemical, the proposed business model contributes to waste reduction, resource efficiency and circular economy objectives. At the same time, it supports the substitution of fossil-based chemicals, thereby reducing greenhouse gas emissions and improving the environmental performance of industrial production systems.

Beyond the environmental benefits, the business model creates additional economic value by generating new revenue streams for starch processing industries and increasing the competitiveness of participating companies. The local valorisation of industrial side-streams also strengthens regional strategic autonomy by reducing dependence on imported fossil-based feedstocks and enhancing supply chain resilience. Furthermore, the production of traceable and sustainable bio-based chemicals enables downstream industries to respond to increasing market demand for low-carbon products and to meet corporate sustainability and ESG objectives.

Customer relationships are primarily based on long-term business-to-business partnerships and strategic collaboration agreements. Given the specialised nature of the product, close interaction with customers is essential. Co-development activities, technical assistance and customised product adaptation may be required to meet the specific needs of downstream applications. Continuous stakeholder engagement through clusters, demonstration projects and industrial networks further supports market development and facilitates the uptake of bio-based solutions.

The primary customer segments include producers of polytrimethylene terephthalate (PTT), manufacturers of bio-based plastics and resins, chemical companies producing solvents and coatings, textile manufacturers, cosmetics companies and other industrial actors seeking sustainable alternatives to fossil-derived chemicals. Companies with ambitious decarbonisation strategies and strong sustainability commitments are expected to represent particularly attractive market segments.

From an economic perspective, the cost structure is dominated by feedstock logistics, pre-treatment operations, fermentation and downstream processing activities. Capital investments in biorefinery infrastructure, research and development activities, labour costs, certification procedures and sustainability reporting activities also contribute significantly to overall costs. Additional costs arise from the coordination and governance requirements associated with industrial symbiosis arrangements.

Revenue generation is primarily based on the commercialisation of bio-based 1,3-Propanediol. Additional revenues may originate from premium pricing associated with renewable and low-carbon products, long-

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term supply agreements, technology licensing, valorisation of additional side-streams and public funding schemes supporting innovation and scale-up activities. Overall, the proposed business model shows strong potential to combine economic competitiveness with environmental sustainability and regional value creation, contributing to the transition to a circular and resilient bioeconomy in Flanders.

The completed Business Model Canvases for all eleven regionally BioLinks are provided in full in Annex 2 of this deliverable.

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5. Life cycle cost

5.1.PHA-Based Biolinks

The modelled production cost is 20.7 EUR/kg for Andalusia and 20.0 EUR/kg for Croatia. Current market pricing for PHA is approximately 2.8 to 5.5 EUR/kg, European (France) spot was around 3.0 USD/kg (≈ 2.8 EUR/kg) in Q4 2025, while high-performance grades and small-volume supply reach 4 to 6 USD/kg, and only high-volume industrial contracts approach 2 to 4 USD/kg (according to IMARC PHA price tracker, Q4 2025; industry B2B pricing guides, 2026). The modelled cost is therefore roughly 4 to 7× the market price (≈7× versus European spot, ≈4× versus premium grades).

The three largest line items account for about 90% of the total cost (89.8% ES, 88.4% CR). (Figure 1 and Figure 2). They sit in three different stages of the value chain:

- Cellulolytic enzymes: 8,950 EUR/t ES / 9,300 EUR/t CR (around half of the cost), in the pre-treatment / enzymatic-hydrolysis stage. This is the single dominant cost: enzyme loading for lignocellulose saccharification is high and priced at 6,580 EUR/t of enzyme.
- DMC extraction solvent: 4,900 EUR/t ES / 5,100 EUR/t CR (around a quarter of the cost), in the bio/chemical-process (PHA extraction) stage. This is already charged at only 5% of the purchase price under the solvent-recovery assumption; even so it is the second-largest item, which shows how solvent-intensive the recovery route is.
- Forestry residues (feedstock): 4,700 EUR/t ES / 3,250 EUR/t CR, in the feedstock-supply stage. Little of the initial biomass sourced as feedstock ends up in the final product (50 t of feedstock per t of product), and therefore it contributes significantly despite the low cost of the feedstock.

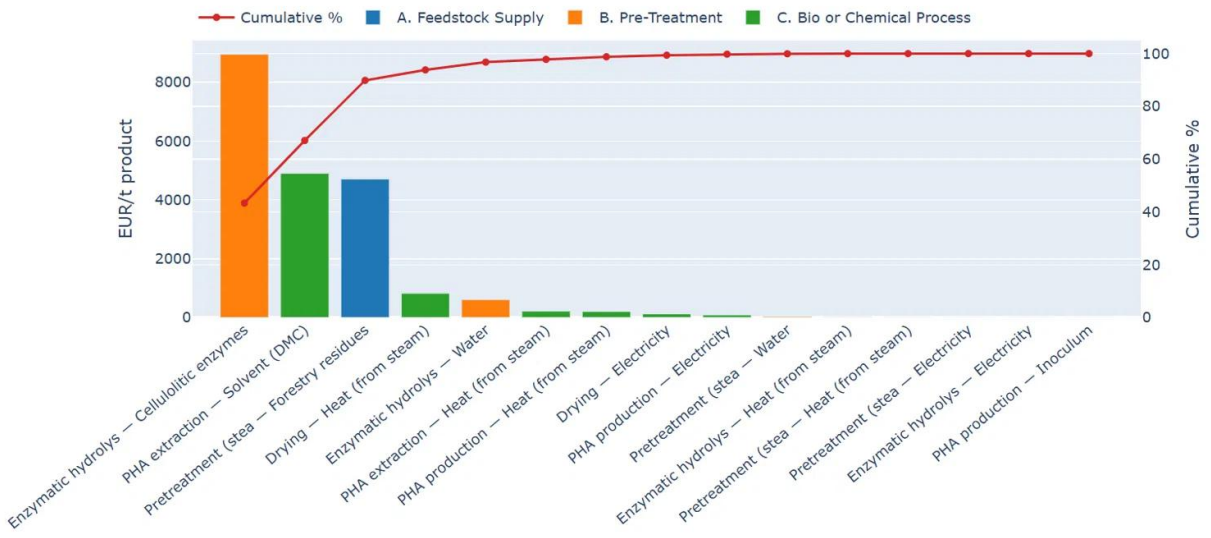

Figure 3. Pareto-type plot of the cost distribution of the LCC of PHA in Spain

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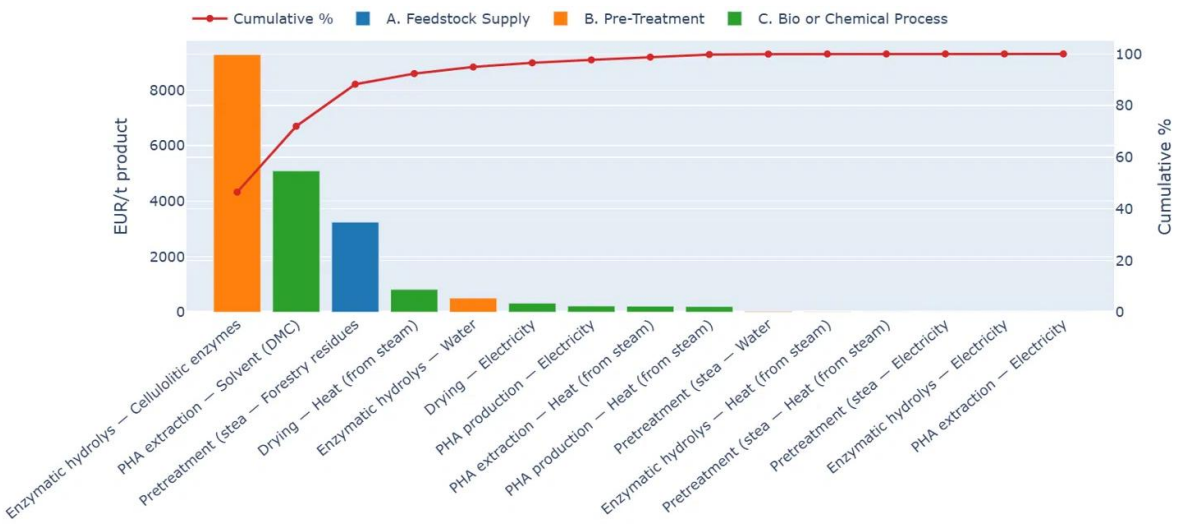

Figure 4. Pareto-type plot of the cost distribution of the LCC of PHA in Croatia.

After the top three, only about 10% of total cost (2,100 EUR/t) remains, distributed across a dozen small items. The largest of these are **drying heat (820 EUR/t, 4.0%) and enzymatic-hydrolysis water (600 EUR/t, 2.9%)**; every other item (extraction and production heat, drying and production electricity, transport, minor water streams) is below 1% individually. These items, along with the rest of the items in the LCC, should not be a priority for optimisation until the first three items (enzymes, DMC extraction, forestry residues) are properly targeted.

5.2.Barley Straw to Succinic Acid

The modelled variable production cost is approximately 5.60 EUR/kg (5,604 EUR/t) for Veneto, Italy, and 5.05 EUR/kg (5,046 EUR/t) for Carinthia, Austria. Reference pricing for industrial-grade succinic acid is approximately 1.08–1.52 EUR/kg, based on the Q3 2025 price indices reported for China, Germany and the United States and converted using the EUR/USD reference rate at the end of September 2025. The most geographically relevant European benchmark is Germany, at approximately 1.43 EUR/kg. The modelled cost is therefore approximately 3.7–5.2 times the wider international price range and approximately 3.9 times the European benchmark for Italy, compared with approximately 3.5 times for Austria.

This gap is plausible for a prospective bio-based production route based on lignocellulosic feedstock, although the comparison should be interpreted cautiously. The principal structural reason is the very high process-water requirement in succinic acid fermentation, combined with acetone-intensive pretreatment and substantial energy demand. The comparison is also conservative because the reported modelled figure represents primarily variable material and utility OPEX. Facility-dependent CAPEX, labour, maintenance, biomass transport, inoculum, wastewater treatment and waste-management costs are not included because no corresponding cost values are provided in the available inventory. Conversely, potential revenues or avoided-cost credits from the acetic acid and formic acid co-products are also excluded.

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The three largest line items account for approximately 80.6% of the calculated variable cost in Veneto:

- Process water for succinic acid production: 3,343 EUR/t of succinic acid (59.7%), located in the core bio or chemical process. This item dominates because approximately 1,276 tonnes of water are required per tonne of succinic acid in the Italian inventory, making the result extremely sensitive to the assumed water requirement and regional water price.
- Acetone for acid pretreatment: 808 EUR/t of succinic acid (14.4%), located in the pre-treatment stage. The contribution is driven by the use of approximately 24.7 tonnes of acetone per tonne of succinic acid and by the assumption that the entire acetone input is purchased rather than recovered and reused.
- Electricity for succinic acid production: 366 EUR/t of succinic acid (6.5%), located in the core bio or chemical process. The contribution reflects an electricity requirement of approximately 2,670 kWh per tonne of succinic acid and is directly sensitive to the regional electricity price.

Overall, the cost is concentrated in the core bio or chemical process, particularly in fermentation water and electricity consumption, followed by solvent use during pretreatment. The dominant water cost is most sensitive to the water-to-product ratio and regional water tariff; the acetone contribution is most sensitive to the solvent-loading and solvent-recovery assumptions; and the electricity contribution is most sensitive to process-energy demand and the regional electricity price.

After the top three, the remaining 19.4%, equivalent to approximately 1,087 EUR/t, is distributed across 10 costed items. The largest remaining contributions are heat for pretreatment, at approximately 302 EUR/t; barley straw, at approximately 296 EUR/t; and heat for succinic acid production, at approximately 236 EUR/t. These contributions are relevant but remain considerably smaller than the process-water hotspot. Optimisation should therefore initially focus on reducing or recycling fermentation water and recovering acetone, followed by improvements in thermal-energy integration. Feedstock and heat costs may justify secondary optimisation, whereas the remaining items form a comparatively low-value tail.

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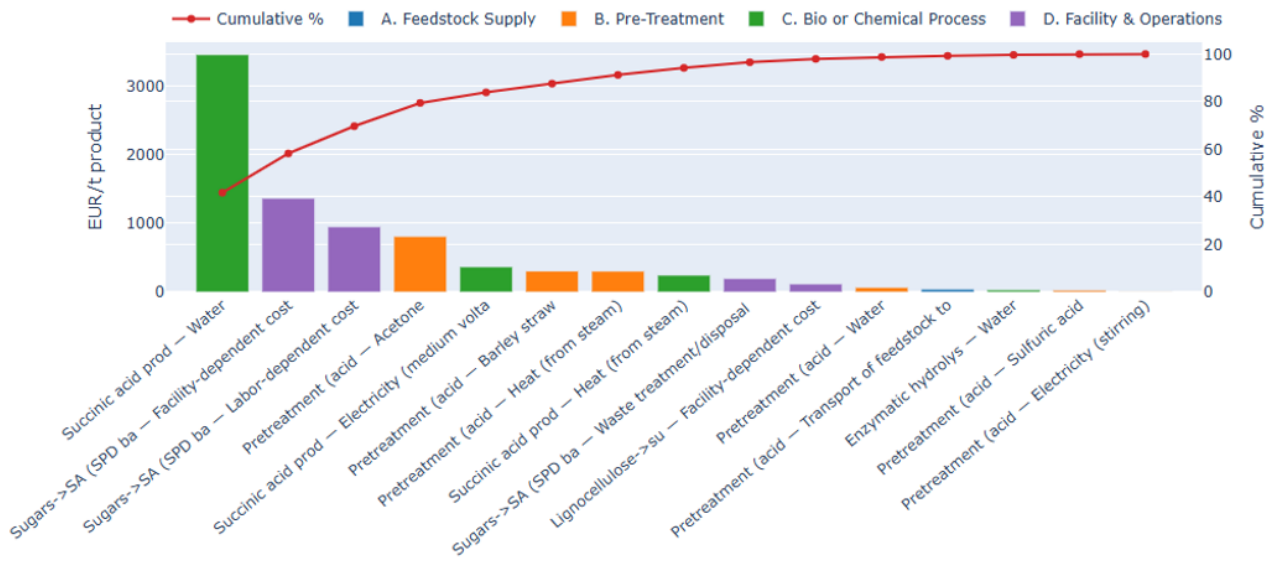

Figure 5. Pareto-type plot of the cost distribution of the LCC of Barley Straw to Succinic Acid process in Italy.

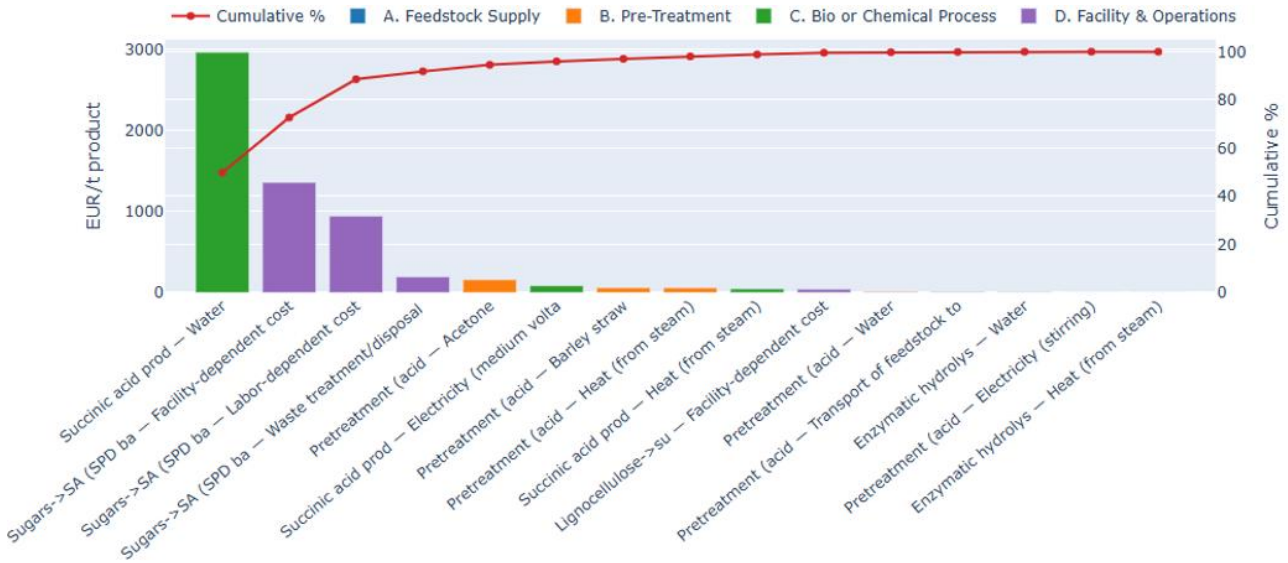

Figure 6. Pareto-type plot of the cost distribution of the LCC of Barley Straw to Succinic Acid process in Austria.

5.3.Corn Residues to Succinic Acid

The modelled variable production cost is approximately 4.61 EUR/kg (4,610 EUR/t) for Piedmont, Italy. Current reference pricing for industrial-grade succinic acid is approximately 1.08–1.52 EUR/kg, based on the Q3 2025 price indices reported for China, Germany and the United States. The most geographically

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relevant available European benchmark is Germany, at approximately 1.43 EUR/kg after conversion from the reported USD price. The modelled cost is therefore approximately 3.0–4.3 times the wider international reference-price range and approximately 3.2 times the German reference price.

This cost gap is plausible for a prospective bio-based route based on lignocellulosic residues, although the comparison should be interpreted cautiously. The principal structural driver is the extremely high process-water requirement attributed to succinic acid production, followed by fermentation electricity demand and the quantity of corn residues required per tonne of final product. The modelled figure represents primarily variable material and utility OPEX. Facility-dependent CAPEX, labour, maintenance, biomass transport, inoculum, wastewater treatment and solid-waste management are excluded because no corresponding cost values are provided in the available inventory. Potential economic credits associated with the acetic acid and formic acid co-products are also excluded.

The three largest line items account for approximately 87.1% of the calculated variable production cost:

- Process water for succinic acid production: approximately 3,335 EUR/t of succinic acid (72.3%), located in the core bio or chemical process. This item dominates because the inventory assumes approximately 1,273 tonnes of process water per tonne of succinic acid, making the result highly sensitive to the assumed water requirement, the proportion of fresh versus recirculated water and the regional water tariff.
- Electricity for succinic acid production: approximately 394 EUR/t of succinic acid (8.5%), located in the core bio or chemical process. This contribution is driven by an electricity requirement of approximately 2,870 kWh per tonne of succinic acid and is directly sensitive to process-energy efficiency and the regional electricity price.
- Corn stovers and straws: approximately 288 EUR/t of succinic acid (6.3%), located in the feedstock supply and pre-treatment stage. This contribution reflects a requirement of approximately 3.21 tonnes of corn residues per tonne of succinic acid and is therefore most sensitive to the assumed biomass-to-product yield and the regional feedstock price.

Overall, the cost is strongly concentrated in the core bio or chemical process, which represents approximately 90.6% of the calculated variable cost, while pre-treatment and feedstock-related inputs represent approximately 9.4%. The process-water hotspot is most sensitive to the water-to-product ratio, water recirculation and regional tariff; the electricity contribution is most sensitive to fermentation-energy demand and electricity price; and the feedstock contribution is most sensitive to the overall conversion yield and the purchase price attributed to corn residues.

After the top three, the remaining 12.9%, equivalent to approximately 593 EUR/t, is distributed across 10 costed items. The largest remaining contributions are heat for succinic acid production, at approximately 236 EUR/t; cellulolytic enzymes, at approximately 169 EUR/t; and heat for acid pretreatment, at approximately 77 EUR/t. Heat for succinic acid production and cellulolytic enzymes are individually relevant enough to justify secondary optimisation, particularly through heat integration, reduced steam demand, lower enzyme loading or enzyme-cost reduction. However, optimisation effort should initially focus on reducing or recirculating process water, followed by fermentation-electricity efficiency and improvement of the overall corn-residue-to-succinic-acid yield.

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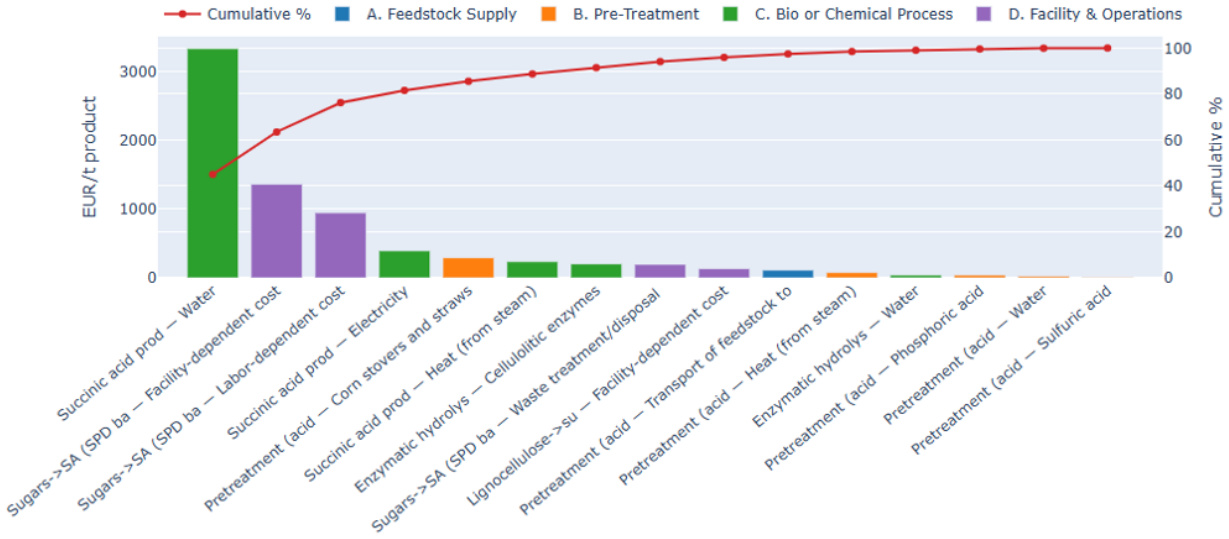

Figure 7. Pareto-type plot of the cost distribution of the LCC of Corn Residues to Succinic Acid process in Italy.

5.4. Corn Steep Liquor to 1,3-Propanediol

The modelled production cost is 4.7 EUR/kg for Belgium. The assessment covers both Flanders and the Brussels-Capital Region, applying a common technological configuration, material-flow inventory and set of Belgian cost assumptions. Current international reference pricing for 1,3-propanediol is approximately 3.2 EUR/kg, based on the Q2 2026 international benchmark. The modelled cost is therefore approximately 1.5× the reference price.

This relatively moderate gap is plausible for an industrially established fermentation route, although the result remains strongly dependent on substrate and feedstock costs. The main structural drivers are the high glycerol requirement, the purchase price of corn steep liquor and the fermentation-water demand. The modelled cost covers feedstock, transport, material and utility OPEX, with transport calculated according to the logistics methodology described in the previous section. Facility-dependent CAPEX, labour, maintenance, wastewater treatment and waste management are excluded. Potential revenues from 2,3-butanediol and lactate are also not credited.

The three largest line items account for approximately 83% of the total modelled cost:

- Glycerol: 2,979 EUR/t of 1,3-PDO (63.8%), in the bio/chemical-process stage. This is the dominant cost because approximately 2.42 t of glycerol are required per tonne of product at a price of 1,230 EUR/t.
- Corn steep liquor: 509 EUR/t (10.9%), in the feedstock-supply / pre-treatment stage. Its contribution is driven by the requirement for approximately 1.45 t of raw corn steep liquor per tonne of 1,3-PDO and an assumed feedstock price of 350 EUR/t.
- Process water: 392 EUR/t (8.4%), in the bio/chemical-process stage. Approximately 121 m^3 of water are required per tonne of product, making this contribution sensitive to fermentation dilution, water recirculation and the Belgian water tariff.

The cost is therefore concentrated in the bio/chemical process, with glycerol supply as the main hotspot. Glycerol is most sensitive to fermentation yield, substrate loading and market price; corn steep liquor is most sensitive to its purchase or transfer price; and process water is most sensitive to dilution and water-reuse assumptions.

After the top three, approximately 17% of total cost, equivalent to 791 EUR/t, remains. The largest secondary contributions are production electricity, at approximately 209 EUR/t, and production heat, at approximately 121 EUR/t, followed by transport and minor pre-treatment utilities. These items should be considered for optimisation only after glycerol use, fermentation yield, corn steep liquor sourcing and process-water demand have been addressed.

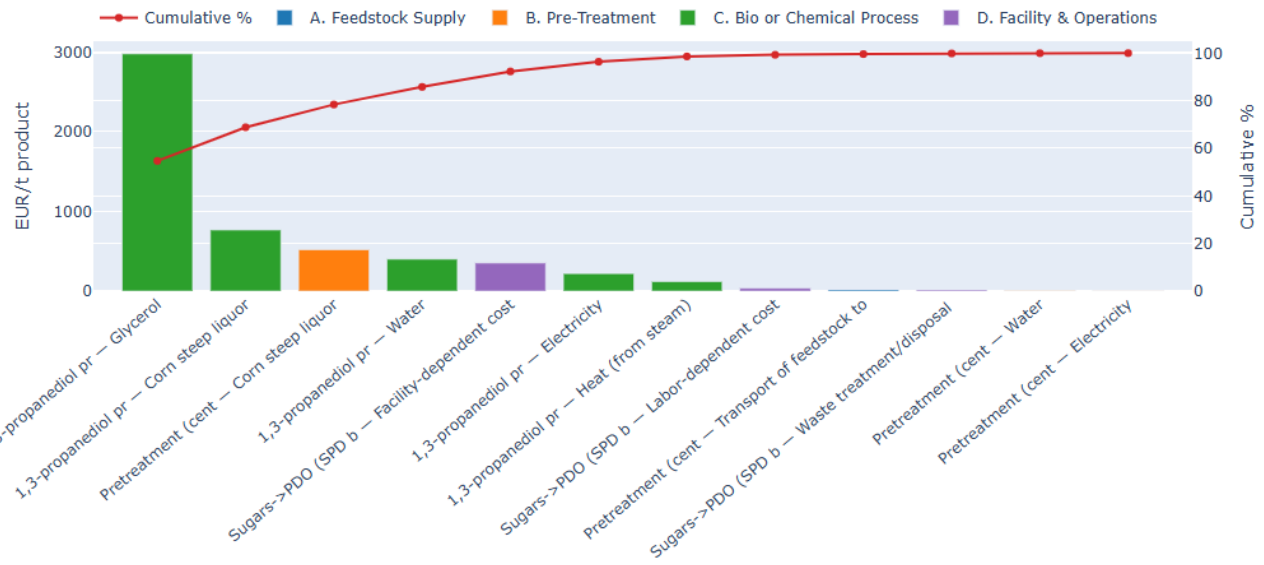

Figure 8. Pareto-type plot of the cost distribution of the LCC of Corn Residues to 1,3-propanediol process in Belgium.

5.5.Wheat Straw to PHA

The modelled production cost is 20.2 EUR/kg for Piedmont, Italy, and 29.2 EUR/kg for Slovenia. Current reference pricing for PHA is approximately 2.7–4.5 EUR/kg, including a European benchmark of around 2.7 EUR/kg for France in Q1 2026 and the 3.5–4.5 EUR/kg range reported in the WOW market-potential study. The modelled cost is therefore approximately 4.5–7.5× the market price in Italy and 6.5–10.8× in Slovenia. This gap is mainly attributable to the high enzyme and ammonia requirements of the lignocellulosic route and the relatively low overall conversion of wheat straw into PHA. The modelled costs cover feedstock, transport, material and utility OPEX, with transport calculated according to the logistics methodology described in the previous section. Facility-dependent CAPEX, labour, maintenance, wastewater treatment and solid-waste management are excluded.

The three largest line items account for approximately 91% of total cost in Italy and 94% in Slovenia. They are concentrated in feedstock supply and pre-treatment:

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- Cellulolytic enzymes: 10,435 EUR/t IT / 10,435 EUR/t SI, representing 51.7% of the Italian cost and 35.8% of the Slovenian cost, in the pre-treatment / enzymatic-hydrolysis stage. This is driven by the assumed enzyme loading of 2.05 t per tonne of PHA and an enzyme price of 5.09 EUR/kg.
- Ammonia for AFEX pretreatment: 5,815 EUR/t IT / 14,794 EUR/t SI, representing 28.8% IT and 50.7% SI, in the pre-treatment stage. Its contribution is driven by an ammonia requirement of 11.38 t per tonne of PHA and is highly sensitive to the regional ammonia price and the assumed level of ammonia recovery and reuse.
- Wheat straw: 2,026 EUR/t IT / 2,162 EUR/t SI, representing 10.0% IT and 7.4% SI, in the feedstock-supply stage. Approximately 11.38 t of straw are required per tonne of PHA, resulting in a significant contribution despite the comparatively low unit cost of the feedstock.

The cost is therefore strongly concentrated in AFEX pretreatment and enzymatic hydrolysis. Enzyme loading and ammonia recovery are the most important technical assumptions, while the regional ammonia-price assumption is the main reason for the higher Slovenian result.

After the top three, approximately 9.4% of the Italian cost, equivalent to 1,894 EUR/t, and 6.1% of the Slovenian cost, equivalent to 1,785 EUR/t, remains across thirteen smaller items. The largest is DMC extraction solvent, at approximately 820 EUR/t in both regions, followed by AFEX heat, PHA-production heat, drying heat and PHA-production electricity, each below approximately 210 EUR/t. DMC consumption and recovery may justify secondary optimisation, but the remaining utilities form a relatively low-value tail and should not be prioritised until enzyme loading, ammonia use and overall biomass-to-PHA yield have been addressed.

The difference between the two regions is primarily driven by the ammonia-price assumptions applied in the model, 511 EUR/t for Italy and 1,300 EUR/t for Slovenia. The comparison should therefore be interpreted mainly as a sensitivity to the regional ammonia benchmark, rather than as evidence of an inherently less competitive Slovenian production pathway.

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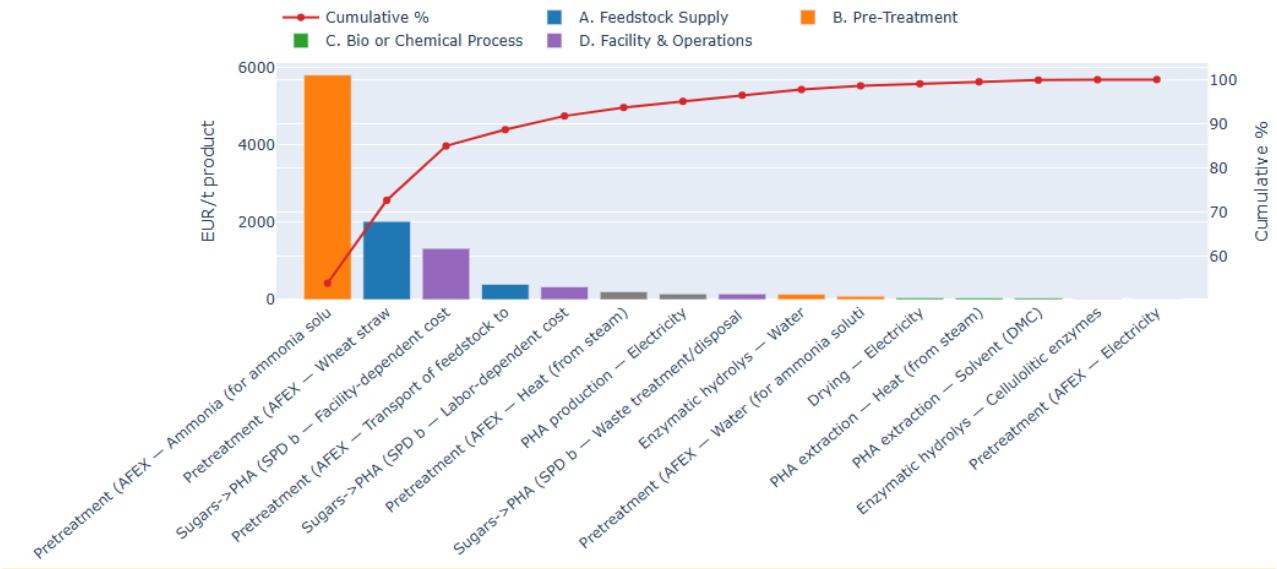

Figure 9. Pareto-type plot of the cost distribution of the WheatStraw to PHA in Italy.

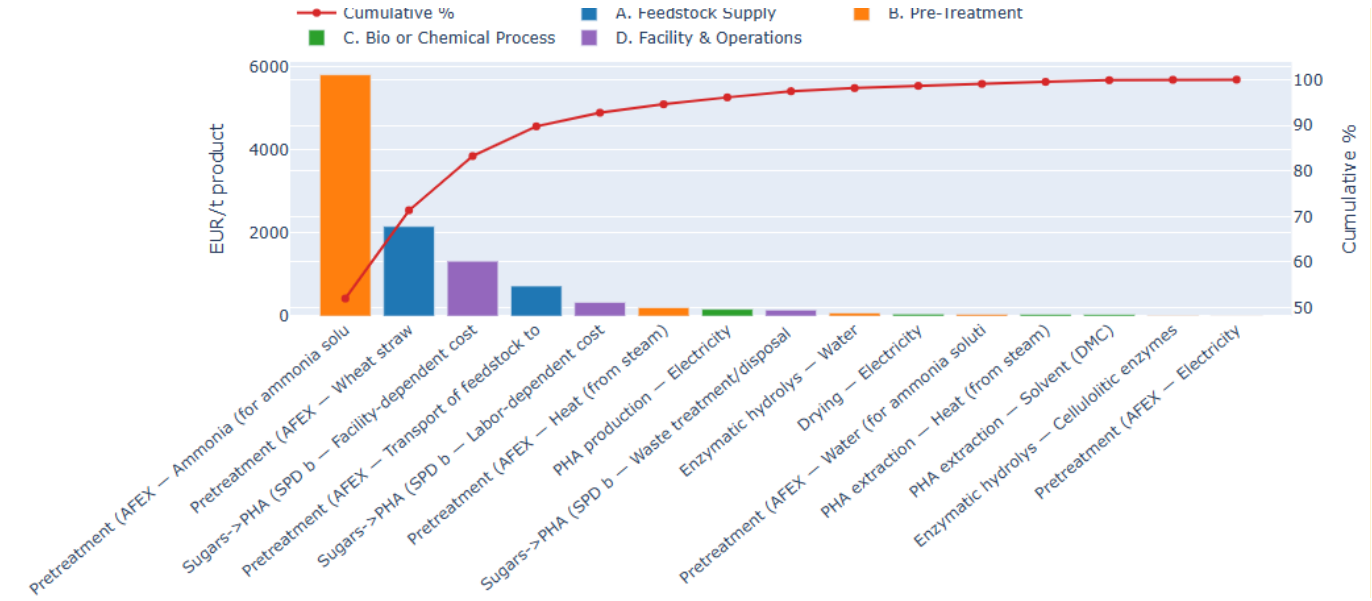

Figure 10. Pareto-type plot of the cost distribution of the WheatStraw to PHA in Slovenia.

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5.6. Whey to protein

The modelled production cost is 0.81 EUR/kg (806 EUR/t) for Friuli Venezia Giulia, Italy, and 0.85 EUR/kg for Wallonia, Belgium. Current European reference pricing for whey protein concentrate varies according to protein content and product grade. European WPC80 was reported at approximately 12.15 EUR/kg in September 2025, while EU export prices for WPC35 ranged from approximately 3.89 to 5.54 EUR/kg during 2025. As the modelled product corresponds to a whey protein concentrate containing approximately 80% protein, the WPC80 price provides the more technically comparable benchmark. The modelled cost is therefore approximately 0.07 times the European WPC80 market price, equivalent to around 7% of the reference value.

The modelled cost is substantially below the market reference price. This result is plausible because raw whey is treated as a low-cost dairy co-product and because the assessment represents mainly process, logistics and utility OPEX rather than a complete minimum selling price. The result is particularly sensitive to the assumed transport distance. Approximately 81 tonnes of raw whey are processed per tonne of whey protein concentrate, meaning that even a relatively short transport distance can have a significant effect on the modelled cost. Facility-dependent CAPEX, labour, maintenance, membrane replacement, packaging and quality-control costs are not explicitly identifiable in the available inventory and should therefore be considered excluded unless incorporated separately in the underlying model.

The three largest line items account for approximately 70.4% of the total modelled cost:

Transport of raw whey to the protein-recovery facility — approximately 390 EUR/t of whey protein concentrate (48.4%), located in feedstock logistics / pre-treatment. This item dominates because the model assumes a transport activity of 3,000.28 t·km per tonne of whey protein concentrate and a regional transport cost of 0.13 EUR/t·km. Its contribution is highly sensitive to the assumed distance between the dairy facility and the protein-recovery plant and could decrease substantially under a co-located industrial-symbiosis configuration.

Heat for evaporation — approximately 105 EUR/t of whey protein concentrate (13.1%), located in the core bio or chemical process. This contribution is driven by an energy requirement of approximately 6,608 MJ per tonne of product and reflects the large amount of water that must be removed from the purified protein stream before final drying. It is most sensitive to the quantity of water removed, evaporator efficiency, heat integration and the assumed steam price.

Heat for spray drying — approximately 72 EUR/t of whey protein concentrate (8.9%), located in the core bio or chemical process. This contribution results from a thermal-energy requirement of approximately 4,500 MJ per tonne of final product. It is most sensitive to the solids concentration entering the spray dryer, the amount of residual water to be removed and the thermal efficiency of the drying operation.

Overall, the cost is concentrated in feedstock logistics and the downstream concentration and drying stages. Transport is most sensitive to plant location and the assumed distance between the whey supplier and the processing facility; evaporation is most sensitive to the volume of water removed and the steam-price assumption; and spray drying is most sensitive to the incoming solids concentration and thermal-energy efficiency. The prominence of transport in the Italian Pareto chart should therefore be interpreted as scenario-dependent. The selected distance represents a hypothetical intra-regional configuration rather

than a uniquely correct value. If the protein-recovery plant were integrated into or located next to the dairy facility, the transport contribution would decrease substantially and evaporation, drying and membrane processing would gain relative importance.

After the top three, the remaining 29.6%, equivalent to approximately 239 EUR/t, is distributed across the other costed inputs. The largest remaining contributions include ultrafiltration electricity, at approximately 69 EUR/t; pasteurisation electricity, at approximately 31 EUR/t; cleaning water for ultrafiltration and diafiltration, at approximately 21 EUR/t; spray-drying electricity, at approximately 14 EUR/t; and diafiltration electricity, at approximately 12 EUR/t. Ultrafiltration electricity is individually relevant enough to justify secondary optimisation through improvements in membrane efficiency, operating pressure and process throughput. The other contributions form a comparatively low-value tail, suggesting that optimisation effort should initially focus on plant co-location or shorter whey-collection distances, followed by heat integration, increased solids concentration before spray drying and improved membrane efficiency.

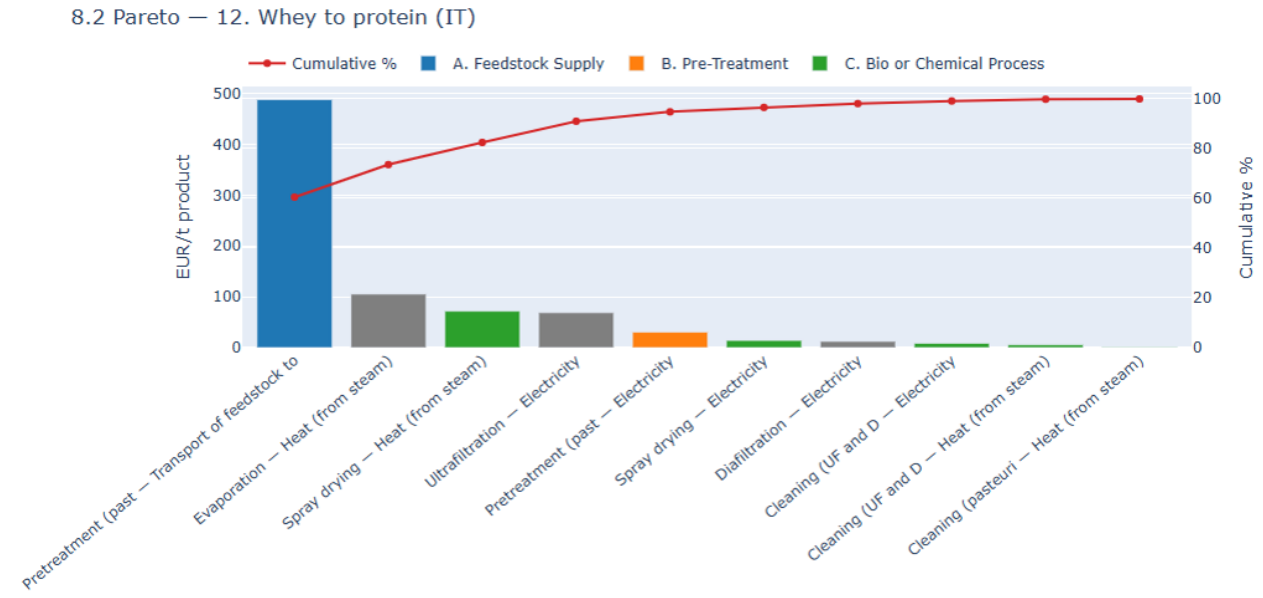

Figure 11. Pareto-type plot of the cost distribution of the LCC of Whey to protein process in Italy

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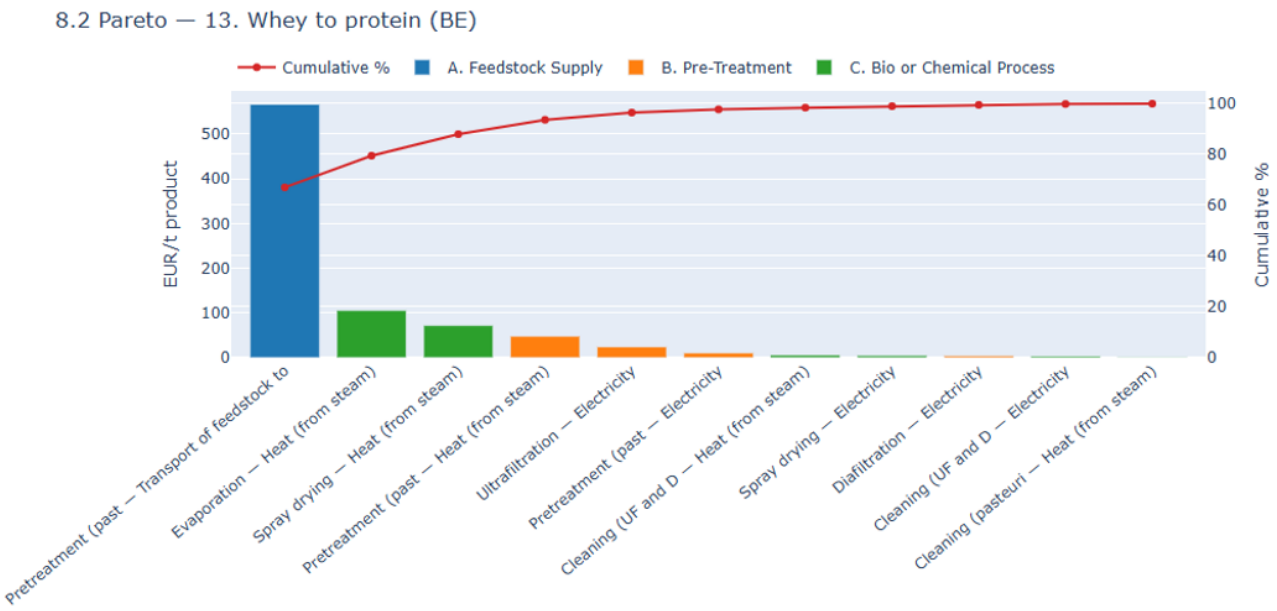

Figure 12. Pareto-type plot of the cost distribution of the LCC of Whey to protein process in Belgium.

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6. Discussion

The economic assessment and Business Model Canvases reveal that the chosen BioLinks are more than just technical conversion methods; they are regionally integrated business models that depend on factors like feedstock supply, conversion efficiency, cost structures, partner engagement, and customer acceptance. In all cases, the Canvases effectively convert technical and cost data into practical operational needs such as coordinating feedstock supply, securing access to conversion and downstream-processing capacity, validating with industrial users, ensuring sustainability documentation, and establishing long-term B2B relationships.

A common observation is that simply having a biomass stream or industrial side-stream does not guarantee its exploitable potential; instead, each situation is limited by various factors such as costs, ecological considerations, and partnership opportunities.

PHA and succinic acid. In lignocellulosic processes, expenses are heavily affected by raw materials and recovery steps. For PHA, production costs are around 20.7 EUR/kg in Andalusia and 20.0 EUR/kg in Croatia, mainly due to cellulolytic enzymes, DMC extraction solvent, and forestry residues, which together make up nearly 90% of total costs. This aligns with the PHA Canvases, which state that PHA "cannot yet be considered a direct drop-in replacement for fossil plastics on cost or, in some applications, performance." For succinic acid, the estimated variable production costs are 4.61 EUR/kg (corn residues, Piedmont), 5.60 EUR/kg (barley straw, Veneto), and 5.05 EUR/kg (barley straw, Carinthia), all exceeding the industrial-grade reference price range used in the assessment. The primary cost driver is process water, followed by electricity, solvent use, or feedstock depending on the route.

For both products, the business logic revolves around targeted applications rather than straightforward commodity replacement. These applications emphasise biodegradability, certification, regional circularity, traceability, and customer-specific formulations, which justify additional validation. The Canvases structure these BioLinks around customers who prioritise "bio-based, traceable and lower-carbon inputs" over price competition with fossil-based options. This alignment between cost analysis and value proposition is crucial: it prevents BioLinks from being seen as mature, low-cost alternatives and instead presents them as promising models that need further optimisation, validation, and customer engagement.

Whey to proteins. This case illustrates a different relationship between costs and the business model. The modelled costs—0.81 EUR/kg in Friuli Venezia Giulia and 0.85 EUR/kg in Wallonia—are below the WPC80 reference price. However, these costs mainly cover process, logistics, and utility OPEX rather than representing a full minimum selling price. Transporting raw whey is the largest expense, requiring about 81 tonnes of raw whey per tonne of whey protein concentrate. The Canvases highlight the importance of aggregation, co-location, and partnerships: in Friuli Venezia Giulia, the main challenge is the fragmented structure of small dairy cooperatives, while in Wallonia, it is the lack of a confirmed ingredient partner and the current practice of sending whey to pig feed or land-spreading.

Corn steep liquor to 1,3-propanediol. This example shows how a single product pathway can involve different regional roles. Flanders centers on industrial biotech capacity, pilot facilities, cluster networks, and direct B2B engagement. In contrast, Brussels, which the Canvas notes as having "very limited biomass production and almost no primary agro-industrial sector," functions more as a hub for coordination, innovation services, brokerage, demonstrations, and sustainability support. This difference is important

for replication: the same BioLink can be adapted to various regional functions based on the local ecosystem assets.

6.1. Comparative insights from the biolinks

Two main implementation profiles are identifiable. The first pertains to residue-based lignocellulosic processes (such as forestry residues for PHA production or corn and barley residues for succinic acid). These involve mobilising dispersed biomass, pretreatment, enzymatic conversion, fermentation, and downstream recovery, forming the core of their business model. Their advantages include the circular utilisation of regional residues, potential for cascade valorisation, and the creation of new connections among agricultural or forestry stakeholders, technology providers, and industrial off-takers. However, their drawbacks involve high costs of key process inputs, the necessity for reliable aggregation systems, and reliance on further technical improvements before market viability can be confidently established.

The second profile focuses on industrial co-product routes such as converting whey to proteins and corn steep liquor to 1,3-propanediol. These routes utilise side-streams already produced by existing industrial processes, resulting in less feedstock uncertainty. However, their implementation depends on factors like location, logistics, processing setup, and the presence of suitable commercial partners. For example, in the whey cases, fragmentation and food-grade processing requirements can limit adoption even when the valorisation potential is promising. Similarly, in CSL cases, the growth of the industrial biotechnology ecosystem and the availability of demonstration infrastructure are critical enabling factors.

Co-products and service-based revenues are noted across various Canvases as possible sources of resilience, yet evidence remains cautious. The succinic acid Canvases list acetic acid, formic acid, lignin-rich residues, and non-fermented sugars, while the PHA Canvases include hemicellulose-derived chemicals, lignin valorisation, biochar, and captured microbial CO2. Since the cost analysis often excludes quantified credits from these streams, their impact on profitability is unconfirmed and should be viewed as potential rather than confirmed revenue streams.

Regional readiness differs across regions. Some BioLinks benefit from more established ecosystems, such as Flanders' biotechnology and pilot infrastructure or Friuli Venezia Giulia's Dairy+ demonstration and knowledge-transfer framework. Others face significant challenges, including Croatia's underdeveloped pilot infrastructure and limited scale-up expertise, or Wallonia's absence of a speciality-ingredient partnership. This illustrates that replication is not simply a matter of transferring a technical solution; it requires tailoring to regional feedstock sources, industrial players, infrastructure, skills, and governance capacity.

6.2. Implications for exploitation, replication and future uptake

Exploitation should follow a phased approach. Several Canvases already mention pilot-to-commercial, sample-to-scale, or technical-validation models, aligning with the cost and uncertainty profile outlined earlier. For PHA and succinic acid, wider adoption depends on reducing key cost drivers before broader commercial use is feasible: for PHA, these include enzyme use, solvent-heavy extraction, and feedstock efficiency; for succinic acid, focus is on water reduction or recirculation, solvent recovery, energy

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efficiency, and increasing yield. In the case of whey to proteins, the main focus is on co-location, shared infrastructure, and collective aggregation, especially where the dairy industry is fragmented. A cooperative, demonstration-based model in Friuli Venezia Giulia, and establishing a credible food-grade ingredient partnership in Wallonia are essential. For CSL to 1,3-propanediol, future adoption relies more on the ability to connect side-stream suppliers, fermentation partners, pilot facilities, and downstream users through coordinated industrial symbiosis, rather than on feedstock seasonality.

Sustainability documentation acts as an additional support, with traceability, MFA/LCA inputs, circularity metrics, ESG support, and certification assistance recurring throughout the Canvases as part of the service or customer relationship. This indicates that BioLinks are expected not only to deliver a bio-based product but also to provide the necessary evidence to justify its adoption—especially when the value proposition emphasises bio-based content, circularity, biodegradability, or regional provenance rather than price.

The main limitation is that several components of the business model are still conditional: some partners and off-takers are only potential, co-product revenues are not fully quantified, and several costs exclude items such as facility-dependent CAPEX, labour, maintenance, waste management, packaging, quality control, and specific replacement costs. Thus, the current analysis offers a preliminary exploitation outline but does not constitute a complete investment case. This qualification is important for objectively interpreting the results and determining the next validation steps.

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7. Conclusions

The chosen BioLinks show feasible circular business-model pathways, but their maturity and readiness for implementation vary greatly. Economic potential relies on factors such as technical performance, cost efficiency, regional ecosystem support, and market engagement. Simply having feedstock isn't sufficient; each BioLink must also have an operational setup that ensures a reliable supply, handles conversion and recovery challenges, mobilises partners, and effectively connects with customers through a credible value proposition.

For the lignocellulosic pathways (PHA, succinic acid), the primary challenge lies in the gap between modelled production costs and current market benchmarks. These BioLinks should be seen as validation-focused opportunities, emphasising optimisation in enzymes, solvents, water, energy, yield, and downstream processing. They offer the most value to customers prioritising bio-based content, traceability, circularity, or biodegradability over the lowest-cost commodity alternatives.

For industrial co-product routes, such as whey to proteins and CSL to 1,3-propanediol, the main obstacles are organisational and ecosystem factors: whey to proteins needs effective aggregation, co-location or shared processing, and partnerships with food-grade ingredient suppliers. Meanwhile, CSL to 1,3-propanediol relies on biotechnology capacity, demonstration infrastructure, and coordination between side-stream suppliers and industrial users. Therefore, replicating these processes in different regions may involve various roles—like production, aggregation, innovation brokerage, demonstration, or sustainability services—rather than a single, transferable model.

Overall, the BioLinks should progress via phased development: pilot validation, engaging customers from sample to scale, confirming partner roles, optimising key cost drivers, clarifying co-product outlets, and strengthening sustainability documentation. The Canvases serve as a useful foundation for this next phase, as they highlight not only the technical value chains but also the partnerships, services, channels, and revenue assumptions that need validation before expanding to larger-scale deployment.

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9. ANNEX 1. LIFE Cycle Inventory

Life Cycle Inventory

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10. ANNEX 2. BUSINESS MODEL CANVAS

Business Model Canvas

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Forestry residues to PHA (Andalusia)

7) Key Partners

•Forestry/sawmill operators and cooperatives in Andalucía (feedstock suppliers).
•Biomasa del Guadalquivir — established regional player already converting organic by-products into succinic acid and PHA; potential strategic partner, technology benchmark, or competitor.
•Research and innovation actors: IFAPA, the Agrifood Campus of International Excellence, and collaborative projects such as ICT-BIOCHAIN.
•Regional government: the Regional Ministry of Agriculture, Fisheries, Water and Rural Development of Andalusia, which owns and funds the ACBS.
•Innovation-support ecosystem: accelerators/incubators, the Andalucía Agrotech Digital Innovation Hub (DIH), and sector platforms such as HortObserTIC and OLEOVALORIZA.
•Downstream industrial partners: plastics compounders and packaging converters (already present in Andalucía with declared interest in biodegradable packaging), plus biomedical and automotive component manufacturers.
•Certification bodies relevant to market trust: TÜV Austria/European Bioplastics (EN 13432 "Seedling" mark), DIN CERTCO, and BPI (for North American market access).
•Technology providers for SSF/SSEH pilot scale-up.
•Visibility/networking platforms: BioSpain, Smart Agrifood Summit, the Andalusia Environment Awards.

6) Product System

•Core product: PHA bioresin/granulate, predominantly short-chain-length (scl-PHA), which holds the largest share of current PHA market value and the fastest projected growth.
•Application-specific formulations: tailored blends for packaging films/bags/containers (largest application segment, ~54–55% of market value), biomedical devices (drug delivery, sutures, scaffolds), automotive trim/insulation, and emerging textile fibre uses. Industry precedent shows producers maintaining large blend portfolios (e.g., 350+ documented PHA formulations) to serve diverse processing methods (injection moulding, blow moulding, film extrusion, extrusion coating).
•Cascade co-products (industrial-symbiosis-enabled diversification):
–Hemicellulose-derived high-value chemicals (e.g., 2,3-butanediol, organic acids).
–Lignin-derived aromatic platform chemicals (e.g., adipic-acid precursors) or direct use of

5) Key Resources

•Regional biomass base: Andalucía generates an estimated ~22.5 million tonnes of forestry residues annually.
•Biorefinery process assets: enzymatic hydrolysis + fermentation infrastructure; optionality on SSF/SSEH for future cost/water/energy efficiency gains.
•Process IP and know-how in pretreatment severity optimisation (a major cost and yield driver).
•Human capital: specialised bioprocess scale-up and fermentation engineering skills — currently flagged as a regional gap.

2) Value Proposition

•Biodegradability across environments: PHA decomposes in soil, marine and industrial composting conditions into water, CO_2 and biomass rather than persisting as microplastics, directly addressing the externalities of conventional plastics.
•Non-food feedstock: using forestry residues as a second-generation feedstock avoids competition with food systems, a clear social and reputational advantage over first-generation (food-crop) PHA and over the "food vs. material" debate around biobased materials.
•Carbon performance: PHA from lignocellulosic biomass is generally regarded as carbon-neutral; some food-waste-based modular production studies report a slightly negative cradle-to-gate GWP (−2.71 kg CO_2-eq/kg PHA) when negative-cost waste feedstocks are used.
•Regional/circular narrative: converts an existing regional waste stream into a higher-value bio-based material, aligning with EU and Andalusian circular-bioeconomy policy priorities and creating a differentiated "regionally-symbiotic" story versus PHA competitors sourced from imported food crops or municipal waste.
•Resilience through diversification: a cascade biorefinery design (PHA + hemicellulose-derived chemicals + lignin valorisation + biochar) provides a value proposition that is not dependent on a single product line, unlike most linear-model competitors.
•Trade-off to manage: PHA cannot yet be considered a direct drop-in replacement for fossil plastics on cost or, in some applications, performance — meaning the value proposition

4) Customer Relationships

•Long-term off-take/supply agreements with compounders and brand owners.
•Co-innovation relationships with biomedical and automotive customers, where qualification cycles are long and collaborative product development is the norm.
•Tiered engagement model: account-managed relationships for large industrial buyers; lighter-touch sample/pilot engagement for SMEs and converters testing new applications, mirroring the "20 kg to 50+ tonnes" scaling model used by existing PHA distributors.
•Collaborative (non-transactional) relationships with regional ecosystem actors — forestry cooperatives, research institutions, and government — given the fragmented and multi-actor nature of feedstock supply.

3) Channels

•Direct B2B sales to plastics compounders and packaging converters already present in Andalucía with stated interest in biodegradable packaging.
•Distribution through bioplastics blenders/distributors for smaller-volume or trial customers.
•Trade fairs and innovation showcases (BioSpain, Smart Agrifood Summit) for visibility and lead generation across agriculture, energy and waste-management sectors.
•Digital/institutional channels: the Andalucía

1) Service Model

•Technical/compounding support: custom PHA blend formulation and processing guidance for converters (injection moulding, film extrusion, blow moulding), mirroring the service layer offered by established PHA distributors.
•Certification and sustainability documentation services: support for customers seeking EN 13432/Seedling, BPI, or equivalent compostability certification, plus carbon-footprint/LCA data to feed brand-owners' ESG disclosures.
•Feedstock-supply coordination service: a symbiosis-brokerage function aggregating and scheduling forestry-residue supply across fragmented regional actors, addressing the logistics gap identified.
•Co-development services: joint R&D engagements with downstream sectors (biomedical, automotive) where application-specific qualification is required before adoption.
•End-of-life guidance: advisory support directing customers and municipalities to appropriate composting/biodegradation routes, given that compostability claims must be substantiated to avoid greenwashing risk.
•Sample-to-scale supply service: tiered offering from small trial volumes (tens of kg) up to multi-tonne industrial supply, lowering adoption risk for new customers, consistent with current market practice.

8) Cost Model

•Feedstock cost: in conventional PHA production, raw materials account for 30–50% (up to 67% in some estimates) of total processing cost. The symbiotic model's core economic lever is replacing purchased food-crop feedstock with a low/negative-cost regional residue stream.
•Pretreatment: typically the largest single cost driver, accounting for roughly one-third of total production cost; severity must be balanced against the formation of fermentation-inhibiting compounds.
•Capital expenditure: biorefinery process equipment; SSF/SSEH technologies could reduce capex through smaller equipment footprints, but as pilot/demonstration-stage technologies they currently carry higher technology and execution risk for an early commercial mover.
•Operating costs — utilities: submerged fermentation (the current commercial standard) requires high water and energy inputs and generates more wastewater than SSF/SSEH alternatives, which can cut water consumption by up to 90%.
•Logistics/aggregation cost: collection and transport of dispersed, seasonal forestry residues (tied to logging cycles), complicated by a limited number of aggregating actors.

9) Revenue Model

•Primary revenue: sale of PHA resin/granulate to compounders and converters; market pricing in the USD 4–6/kg range generally, with specialty/blended-grade pricing observed as high as EUR 7–20/kg depending on formulation and order volume.
•Secondary/diversified revenue (industrial-symbiosis upside):
–Hemicellulose-derived chemicals (2,3-butanediol, organic acids) sold into chemical-industry value chains.
–Lignin-derived aromatic chemicals or lignin-reinforced PHA composites, monetising what is otherwise the largest waste stream of the process (~81% of biomass input).
–Biochar sales for carbon sequestration, soil amendment or energy markets.
–Carbon-credit or merchant CO_2 revenue from captured microbial emissions.
•Service-based revenue: compounding-as-a-service/custom formulation fees; sustainability and LCA reporting services for brand-owner clients.
•Policy-linked revenue support: grants and subsidies under the ACBS and EU bioeconomy/circular-economy funding instruments, materially relevant during the pilot/early-commercial phase even though not strictly "market" revenue.

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Forestry residues to PHA (Croatia)

7) Key Partners

•Croatian forestry/sawmill operators and the national timber industry (feedstock suppliers).
•Bio-Mi d.o.o. — potential strategic partner or technology benchmark; already operates EU-funded R&D projects on bio-based packaging materials (BIOnTOP, USABLE PACKAGING, ECOFUNCO) that overlap directly with PHA-adjacent application development.
•Agroproteinka d.d. — relevant ecosystem peer demonstrating mature regional logistics for by-product collection (50+ specialised vehicles, national network of collection points) and waste-to-value conversion, even though its feedstock (animal by-products) differs from forestry residues.
•Research and innovation actors: University of Zagreb faculties (Chemical Engineering and Technology; Forestry and Wood Technology; Agriculture; Food Technology in Osijek), Croatian Forest Research Institute, Ruđer Bošković Institute, Energy Institute Hrvoje Požar, Agricultural Institute Osijek.
•Business/innovation support ecosystem: the Business Innovation Centre of Croatia (BICRO), Startup Factory Zagreb/ZICER, Crohub, HAMAG-BICRO, the Croatian Association of Employers (HUP), and the Croatian Chamber of Economy.
•Sector promotion bodies: the Croatian Biomass Association (CROBIOM), the Innovation Council on Food and Bioeconomics, CroBiohub, and the Green Energy Cooperative.
•Downstream industrial/market partners: 109 active bioeconomy businesses in Croatia, including multinational consumer-goods companies (Heineken, Coca-Cola) and 123 actors organised in clusters, cooperatives and producer groups — a sizeable potential customer/partner base for packaging applications.
•Policy partners: relevant national ministries

6) Product System

•Core product: PHA biopolymer granulate, predominantly short-chain-length (scl-PHA), holding the largest share of current global PHA market value and the fastest projected growth.
•Application-specific formulations: packaging films/bags/containers (the largest global application segment, ~54–55% of market value) — a segment where Croatia already has a credible national reference point via Bio-Mi's certified packaging and agro-application films — plus biomedical devices, automotive trim/insulation, and emerging textile fibre uses.
•Cascade co-products (industrial-symbiosis-enabled diversification):
–Hemicellulose-derived high-value chemicals (e.g., 2,3-butanediol, organic acids).
–Lignin-derived aromatic platform chemicals (e.g., adipic-acid precursors) or direct use of lignin as a reinforcing filler within PHA composites, cutting raw-material cost and

5) Key Resources

•National biomass base: a reported forestry residue stream of 3,096,636 tonnes/year — the largest single industrial by-product category identified in Croatia, ahead of municipal solid waste (427,896 t) and paper/tissue waste (333,200 t).
•Active timber/forestry sector as the structural source of feedstock continuity, though availability is seasonal (tied to logging cycles and weather).
•Existing process know-how in compostable thermoplastics, embodied in Bio-Mi's certified MI-blend materials and four years of dedicated R&D investment {22}{23} — a transferable regional knowledge base, even though not yet PHA-specific.
•Academic/research infrastructure: University of Zagreb (Faculty of Chemical Engineering and Technology; Faculty of Forestry and Wood Technology; Faculty of Agriculture), Croatian

2) Value Proposition

•Biodegradability across environments: PHA decomposes in soil, marine and industrial composting conditions into water, CO2 and biomass rather than persisting as microplastics.
•Non-food, non-land-competing feedstock: forestry residues fully avoid competition with food systems, addressing both the "food vs. material" debate and Croatia's emphasis on protecting soil quality and forest ecosystem function.
•Carbon performance: PHA from lignocellulosic biomass is generally regarded as carbon-neutral; however, environmental performance is "highly sensitive to process design," particularly pretreatment, which can account for up to 33% of total production cost and materially affects overall sustainability.
•National/regional bioeconomy narrative: converts an existing national forestry by-product stream into a higher-value bio-based material, aligning directly with Croatia's National Development Strategy, Smart Specialisation Strategy, and BIOEAST commitments, and building on an already-proven national precedent (Bio-Mi's certified compostable thermoplastics).
•Resilience through diversification: a cascade biorefinery design (PHA + hemicellulose-derived chemicals + lignin valorisation + biochar) avoids dependence on a single product line.
•Trade-offs to manage: (i) PHA is not yet a direct drop-in replacement for fossil plastics on cost or, in some applications, performance; (ii) in Croatia specifically, the value proposition must also account for competition for the same residue streams from the energy-recovery sector, and for documented consumer resistance to price premiums for bio-based products.

4) Customer Relationships

•Long-term off-take/supply agreements with compounders and brand owners, following international industry precedent (e.g., RWDC's long-term R&D partnership with the University of Georgia; Newlight's 2025 production agreement with Long Ridge Energy Terminal).
•Co-innovation relationships with Croatian research institutions (University of Zagreb, Ruđer Bošković Institute) to accelerate the transition from lab-scale to industrial-scale PHA production.
•Tiered engagement model: account-managed relationships for larger industrial buyers (e.g., the multinational consumer-goods companies already active in Croatia's bioeconomy sector, such as Heineken and Coca-Cola); lighter-touch sample/pilot engagement for SMEs and converters testing new applications, mirroring the "20 kg to 50+ tonnes" scaling model used by existing PHA distributors.

3) Channels

•Direct B2B sales to packaging converters and downstream industries already aligned with biodegradable materials in Croatia.
•Distribution through bioplastics blenders/distributors for smaller-volume or trial customers.
•Industry-association channels: CROBIOM workshops/conferences and the Croatian Chamber of Economy's business-support events as a channel for visibility and lead generation.
•Digital/institutional channels: Digital Innovation Hub Croatia, connecting businesses with technology providers and researchers.
•Policy/institutional channel: engagement through national funding mechanisms (OPCC, Integrated Territorial Program, CAP Strategic Plan 2023–2027) and the BIOEAST network for cross-border partnership and incentive access.

1) Service Model

•Technical/compounding support: custom PHA blend formulation and processing guidance for converters, mirroring the service layer offered by established PHA distributors.
•Certification and sustainability documentation services: support for customers seeking EN 13432/Seedling, BPI, or equivalent compostability certification — a route already validated nationally by other distributors.
•Feedstock-supply coordination service: a dedicated symbiosis-brokerage function to separate and channel forestry residues away from competing energy-recovery uses.
•Co-development services: joint R&D engagements with University of Zagreb faculties and research institutes to bridge the identified lab-to-industrial-scale gap.
•End-of-life guidance: advisory support on appropriate composting/biodegradation routes, important given Croatia's significant tourism-driven sensitivity to plastic pollution in coastal/marine environments.
•Sample-to-scale supply service: tiered offering from trial volumes up to industrial supply, consistent with current PHA-market practice.

8) Cost Model

•Feedstock cost: raw materials typically account for 30–50% (up to 67% in some estimates) of total PHA processing cost; the symbiotic model's core lever is substituting purchased feedstock with a low/negative-cost regional residue stream — though in Croatia this advantage is partly offset by the need to actively separate residues from the energy-recovery stream during collection, which is not a comparable cost in regions without that competition.
•Pretreatment: the largest single cost driver, accounting for roughly one-third of total production cost; severity must be balanced against the formation of fermentation-inhibiting compounds.
•Capital expenditure: Croatia's source material is explicit that large-scale industrial infrastructure for bio-based chemicals (PHA, succinic acid, sorbitol, glycerol) is still underdeveloped, implying a higher relative capex/first-mover burden than in regions with more mature pilot infrastructure.
•Operating costs — utilities: submerged fermentation (the current commercial standard) requires high water and energy inputs; SSF/SSEH alternatives could cut water consumption by up to 90% but remain mainly at pilot scale.
•Logistics/aggregation cost: collection and transport of dispersed, seasonal forestry residues, complicated in Croatia by the

9) Revenue Model

•Primary revenue: sale of PHA resin/granulate to compounders and converters; market pricing in the USD 4–6/kg range generally, with specialty/blended-grade pricing observed as high as EUR 7–20/kg depending on formulation and order volume.
•Secondary/diversified revenue (industrial-symbiosis upside):
–Hemicellulose-derived chemicals (2,3-butanediol, organic acids) sold into chemical-industry value chains.
–Lignin-derived aromatic chemicals or lignin-reinforced PHA composites, monetising what is otherwise the largest non-PHA output stream of the process.
–Biochar sales for carbon sequestration, soil amendment or energy markets.
–Carbon-credit or merchant CO2 revenue from captured microbial emissions.
•Service-based revenue: compounding-as-a-service/custom formulation fees; sustainability/LCA reporting services for brand-owner clients (a precedent already exists nationally via Bio-Mi's compostable-materials business).
•Policy-linked revenue support: national and EU funding instruments specifically available to Croatian bioeconomy projects

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Barley straw to succinic acid (Veneto, Italy)

7) Key Partners

• Barley producers, cereal growers, agricultural cooperatives and straw aggregators in Veneto as primary feedstock suppliers for the barley-straw stream .
• Cereal and barley supply-chain actors identified in D2.2, including Cereal Docks S.p.A., Birra Peroni S.r.l. and Birra Castello S.p.A.; these actors should be treated as barley supply-chain or aggregation interfaces rather than confirmed direct straw producers .
• Technology and processing partners for lignocellulosic pretreatment, enzymatic hydrolysis, fermentation, CO2 handling and downstream purification. D2.2 indicates a limited technology-provider base for this route, making pilot/demo capacity a key partnership need .
• Chemical and biotech integrators in Veneto, including the Porto Marghera industrial ecosystem and Eni as a possible integrator if bio-based chemical activities are developed.
• Industrial off-takers in polymers, resins, coatings, solvents and packaging, especially users of bio-based succinic acid and PBS-related materials.
• Logistics operators specialised in collection, baling, seasonal storage and transport of low-bulk-density agricultural residues .
• Regional authorities, clusters, chambers of commerce and innovation-support organisations able to facilitate industrial symbiosis, farmer engagement, partner validation and access to public support mechanisms .

6) Product System

• Collection, baling, aggregation and controlled storage of barley straw generated during Veneto's seasonal harvest window .
• Feedstock conditioning and acid-based pretreatment to open the lignocellulosic structure and improve cellulose/hemicellulose accessibility.
• Enzymatic hydrolysis to release fermentable C5/C6 sugars from barley straw .
• Microbial fermentation of sugars into bio-succinic acid, with nutrient inputs such as corn steep liquor and potential CO2 assimilation during fermentation .
• Downstream processing, separation, crystallisation/membrane-based recovery or other purification steps to obtain industrial-grade succinic acid. This is a critical activity because recovery and purification are major cost drivers for fermentative succinic acid routes .

5) Key Resources

• Regional biomass base: D3.2 estimates around 80,160 t of barley straw in Veneto for this value chain, plus a separate remaining barley harvest stream of around 67,464 t.
• Lignocellulosic feedstock characteristics: barley straw is rich in cellulose and hemicellulose, making it suitable for saccharification and fermentation into succinic acid .
• Biorefinery assets for pretreatment, enzymatic hydrolysis, fermentation, CO2 handling, downstream processing and co-product management .
• Process know-how in lignocellulosic pretreatment, microbial fermentation, impurity management and succinic acid purification .
• Storage and logistics infrastructure to manage seasonality, low bulk density,

2) Value Proposition

• Conversion of a regional agricultural residue into a higher-value platform chemical, shifting barley straw from low-value or traditional uses toward a circular bio-based business model.
• Production of bio-based succinic acid as a chemical intermediate for biodegradable plastics such as PBS, resins, polyurethanes, coatings, solvents, food-related uses, pharmaceuticals and cosmetics .
• Strong circularity narrative: local lignocellulosic biomass replaces fossil-based feedstocks and connects agriculture, logistics, biotechnology and chemical markets through industrial symbiosis.
• Climate and resource-efficiency potential through fossil-feedstock substitution and fermentation routes that can assimilate CO2 during succinic acid production .
• Regional value creation in Veneto through new outlets for cereal residues, rural income diversification and integration with chemical/biotech capabilities .
• Revenue-resilience potential from co-products such as acetic acid, formic acid and lignin-rich residues, provided that quality and offtake routes are secured .
• Main trade-off: the value proposition is not based on immediate commodity price parity. Bio-succinic acid remains challenged by high downstream processing costs, capital intensity and price competition with petrochemical routes, so the strongest fit is with customers valuing bio-based, traceable and lower-carbon inputs.

4) Customer Relationships

• Long-term B2B offtake agreements with chemical, polymer, resin, coating and packaging customers that require predictable quality and supply .
• Co-development relationships with downstream users to validate bio-succinic acid in PBS, polyurethane, coating, solvent and specialty chemical formulations .
• Feedstock-supply agreements with farmers, cooperatives and cereal-chain actors covering price, harvest timing, moisture, storage, quality and logistics responsibilities.
• Cluster-mediated relationships through regional agricultural, chemical and innovation networks to reduce coordination costs across a fragmented multi-actor value chain .

3) Channels

• Direct B2B sales to chemical manufacturers, polymer producers, packaging converters, coating/resin formulators and other industrial off-takers .
• Regional industrial symbiosis platforms, agricultural associations and cluster networks that can connect feedstock suppliers, technology providers and buyers .
• Pilot and demonstration projects to validate process yields, quality performance, product specifications and co-product routes before commercial scale-up .
• Trade fairs and sector networks in bio-based chemicals, bioplastics, packaging, coatings and circular economy as visibility and lead-generation channels .

1) Service Model

• Integrated B2B service combining bio-based succinic acid supply, technical support, industrial-symbiosis coordination and sustainability documentation .
• Feedstock-supply coordination service aggregating barley straw from dispersed agricultural actors and organising seasonal collection, storage and delivery to the biorefinery .
• Sample-to-scale service model allowing chemical, polymer and packaging customers to validate bio-succinic acid before entering larger-volume supply agreements .
• Co-development and application-support services for PBS, coatings, resins, polyurethanes and specialty chemical uses .
• Sustainability documentation package, including traceability, MFA/LCA inputs, circularity indicators and potential support for ESG or bio-based procurement requirements .
• Industrial symbiosis brokerage service connecting feedstock producers, logistics actors, conversion partners and industrial off-takers within Veneto's regional ecosystem .
• Advisory support for residue management and co-product valorisation, especially lignin-rich residues, acetic acid, formic acid and non-fermented sugars.

8) Cost Model

• Feedstock acquisition, collection, baling, aggregation, storage and transport costs; straw logistics are structurally relevant because of low bulk density, seasonality and the need for continuous biorefinery operation .
• Farmer compensation and contractual costs, including the need to compete with soil incorporation, animal bedding, roughage and other established straw uses .
• Pretreatment costs: acid, process water, energy, corrosion-resistant equipment and handling of inhibitors generated during lignocellulosic processing .
• Enzymatic hydrolysis costs, including enzymes and controlled saccharification conditions .
• Fermentation costs, including nutrients such as corn steep liquor, utilities, microbial process control, CO2 management and quality monitoring .
• Downstream processing and purification costs, highlighted in the evidence as one of the main cost barriers for fermentative succinic acid; D3.2 indicates that recovery/purification can represent a dominant share of total production cost .
• CAPEX for pretreatment, fermenters, purification systems, storage infrastructure, utilities and co-product handling .
• Certification, REACH/chemical compliance, food-contact documentation where relevant, product quality assurance and sustainability reporting costs .
• Coordination and governance costs across farmers, logistics operators, technology providers, biorefinery operators and industrial off-takers.

9) Revenue Model

• Primary revenue from sales of bio-based succinic acid to chemical, polymer, resin, coating, solvent, packaging and specialty chemical markets.
• Long-term supply contracts with industrial customers seeking renewable, bio-based or lower-carbon chemical intermediates .
• Premium or preferred-procurement value linked to bio-based content, traceability, circularity, reduced fossil dependency and regulatory/customer pressure for greener materials; this remains contingent on customers accepting a higher-cost bio-route .
• Co-product revenue from acetic acid and formic acid, both identified in the Veneto MFA, subject to purity, recovery economics and market access .
• Potential value from lignin-rich residues via energy recovery, process heat integration or further material valorisation, depending on local technical and market conditions .
• Potential process-efficiency upside from non-fermented sugars if future optimisation enables additional conversion or internal recycling {3}{6}.
• Service-based revenue from technical validation, sustainability documentation, traceability, LCA/MFA inputs, circularity reporting and customer support .
• Public innovation grants, demonstration funding or regional/EU scale-up support may help de-risk early deployment, but no specific Veneto funding scheme for this BioLink was confirmed in the provided SYMBIO documents.

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Barley straw to succinic acid (Carinthia, Austria)

7) Key Partners

• Local grain and straw producers in Carinthia as the primary suppliers of barley straw for the BioLink.
• Agricultural cooperatives, straw aggregators and logistics operators able to organise collection, baling, seasonal storage and transport of dispersed, low-bulk-density straw .
• AGRANA Stärke GmbH and Beta Pura GmbH, identified in D2.2 as processing/conversion actors for the Carinthia route .
• Mondi Frantschach GmbH as a potential biodegradable-packaging off-taker and Treibacher Industrie as a potential chemical-application off-taker .
• Green Tech Valley and related Carinthian green-technology/circular-economy actors as ecosystem enablers for scale-up, demonstration and industrial symbiosis .
• Technology providers for lignocellulosic pretreatment, enzymatic hydrolysis, fermentation, CO2 management and downstream purification .
• Regional authorities, innovation agencies and public-support organisations able to facilitate demonstration, stakeholder coordination and circular-bioeconomy deployment.

6) Product System

• Seasonal collection, baling, aggregation and storage of barley straw.
• Feedstock conditioning and pretreatment to open the lignocellulosic structure and improve sugar accessibility.
• Enzymatic hydrolysis to release fermentable C5/C6 sugars from cellulose and hemicellulose.
• Microbial fermentation of sugars into succinic acid, supported by nutrient inputs such as corn steep liquor and by CO2 fixation as represented in the MFA .
• Downstream processing, recovery, purification and quality control of succinic acid, a decisive cost and scale-up bottleneck for fermentation-based routes.
• Management of acetic acid, formic acid, lignin residues, non-fermented sugars and other residual streams.
• MFA/LCA-based monitoring, traceability and circularity documentation for customers and regional stakeholders.

5) Key Resources

• Regional biomass base: D3.2 reports 16,058 t of barley straw input for the Carinthia MFA scenario and around 10,616 t of remaining barley harvest.
• Existing regional value-chain actors identified in D2.2: AGRANA Stärke GmbH and Beta Pura GmbH for processing/conversion, and Mondi Frantschach GmbH and Treibacher Industrie as potential market anchors.
• Lignocellulosic feedstock suitable for pretreatment, hydrolysis and fermentation into succinic acid .
• Biorefinery assets for pretreatment, enzymatic hydrolysis, fermentation, CO2 handling, purification and co-product management.
• Green Tech Valley and Carinthian green-technology capabilities as ecosystem resources for scale-up, climate-tech positioning and circular-economy collaboration .
• Renewable-energy and CHP integration potential, relevant to the Carinthia cost and environmental case .
• MFA datasets and conversion assumptions from D3.2, including acid,

2) Value Proposition

• Valorisation of barley straw into bio-based succinic acid, transforming a secondary agricultural residue into a higher-value platform chemical.
• Use of a non-food lignocellulosic feedstock, reducing reliance on fossil-based succinic acid while avoiding direct competition with main barley-grain uses .
• Bio-based intermediate for biodegradable polymers such as PBS, packaging applications, resins, polyurethanes, coatings, solvents and speciality chemicals.
• Strong industrial-symbiosis narrative: the model connects local agriculture, biomass logistics, conversion actors, renewable-energy potential and downstream chemical/packaging markets.
• Environmental value from fossil-feedstock substitution, potential CO2 assimilation during fermentation and lignin-residue use for process energy in integrated biorefinery configurations.
• Regional differentiation: Carinthia benefits from renewable-energy availability and Green Tech Valley-type capabilities, but must manage mountainous logistics and competing straw uses.
• Trade-off to manage: bio-succinic acid remains cost-sensitive, so the strongest value proposition targets customers valuing traceability, bio-based content and low-carbon positioning rather than lowest-price commodity supply.

4) Customer Relationships

• Long-term B2B offtake relationships with chemical, polymer, resin, coating and packaging customers that require reliable quality and traceability .
• Co-development with potential users such as Mondi Frantschach GmbH and Treibacher Industrie to validate end-use performance in packaging, polymer or chemical applications .
• Collaborative feedstock agreements with grain and straw producers covering harvest timing, quality, moisture, storage responsibilities and price conditions .
• Cluster-mediated relationships through Carinthian green-technology and circular-economy networks to support partner mobilisation and regional legitimacy .
• Technical and sustainability-support relationships, including MFA/LCA inputs, carbon-footprint data, bio-based content evidence and circularity documentation .
• Sample-to-scale engagement, because the evidence points to

3) Channels

• Direct B2B sales to chemical companies, biodegradable-packaging producers, polymer producers, coating/resin formulators and speciality-chemical users .
• Regional innovation and circular-economy channels, including Green Tech Valley-type networks, for partner identification, demonstration and validation .
• Agricultural cooperatives, straw aggregators and local producer networks as feedstock-supply channels .
• Pilot facilities and demonstration projects as market-development channels before larger-volume adoption.
• Sector platforms and trade fairs in bio-based chemicals, bioplastics, packaging, coatings and circular economy, used as recommended market-entry channels consistent with the completed BMC examples.
• Institutional channels linked to circular bioeconomy, renewable energy and industrial decarbonisation, especially where public

1) Service Model

• Integrated B2B service combining bio-based succinic acid supply, technical support, feedstock coordination and sustainability documentation .
• Feedstock-supply coordination service aggregating barley straw from dispersed local producers and scheduling collection, storage and delivery to conversion facilities .
• Pilot-to-commercial validation service for customers testing the product in PBS, coatings, resins, polyurethanes, packaging or speciality chemical applications .
• Industrial symbiosis brokerage connecting farmers, straw aggregators, conversion partners, Green Tech Valley-type ecosystem actors and off-takers .
• Co-product valorisation advisory for acetic acid, formic acid, lignin residues and non-fermented sugars, improving resilience beyond a single-product model .
• Sustainability documentation package, including traceability, MFA/LCA inputs, circularity evidence and regulatory/customer-support documentation .

8) Cost Model

• Feedstock collection, baling, aggregation, storage and transport costs, with additional pressure from low straw bulk density and Carinthia's topography .
• Feedstock opportunity cost and farmer compensation, especially due to competing uses such as bedding, roughage and mushroom compost markets .
• Pretreatment costs, including acid input, process water, energy, equipment and inhibitor management .
• Enzyme, nutrient and fermentation costs, including CSL input, utilities, CO2 management, broth handling and quality monitoring .
• Downstream recovery and purification costs, a major economic bottleneck for fermentation-based succinic acid .
• CAPEX for pretreatment units, fermenters, storage facilities, purification systems, co-product handling and possible CHP/energy-integration equipment.
• Certification, regulatory compliance, quality assurance, REACH/substance documentation and sustainability reporting costs .

9) Revenue Model

• Primary revenue from sales of bio-based succinic acid to chemical, polymer, coating, resin, solvent and packaging markets .
• Long-term supply contracts with industrial customers seeking renewable, traceable or lower-carbon chemical intermediates.
• Preferred-procurement or premium-value positioning linked to bio-based content, circularity and reduced fossil-resource dependence, although cost competitiveness remains a constraint.
• Co-product revenue from acetic acid and formic acid, subject to recovery economics and product-quality requirements .
• Potential value from lignin-rich residues via CHP, process heat, electricity generation or other valorisation routes.
• Potential process-efficiency upside from non-fermented sugars if future optimisation enables further conversion or internal recycling.
• Service-based revenue from technical validation, sustainability documentation, MFA/LCA inputs, traceability and circularity reporting support.
• Public innovation or demonstration funding may help de-risk early deployment, but no specific Carinthia funding scheme was confirmed in the provided SYMBIO documents.

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Corn Steep Liquor (CSL) → 1,3-Propanediol (1,3-PDO) for Flanders (Belgium)

7) Key Partners

Corn wet milling and starch processing companies generating Corn Steep Liquor as a by-product.
Industrial biotechnology companies specialised in microbial fermentation and downstream processing.
Flemish bioeconomy and industrial biotechnology clusters (e.g., Catalisti, Flanders' FOOD).
Research and technology organisations (Ghent University, VITO, VIB, Bio Base Europe Pilot Plant).
Bio Base Europe Pilot Plant and other shared biorefinery infrastructure operators.
Logistics providers specialised in handling liquid biomass and industrial side-streams.
Chemical manufacturers and polymer producers using bio-based intermediates.
Industrial symbiosis facilitators and circular economy platforms supporting material exchanges.
Equipment suppliers for fermentation, separation and purification technologies.
Regional authorities, funding agencies and innovation support organisations.
Industrial off-takers from the polymer, textile, cosmetics, coatings and chemical sectors.

6) Product System

Collection, storage and logistics management of Corn Steep Liquor from regional agro-industrial facilities.
Pre-treatment and conditioning of CSL for microbial fermentation.
Fermentative conversion of CSL into 1,3-Propanediol through biotechnological processes.
Downstream processing, purification and quality control of 1,3-PDO.
Process optimisation to improve yields, productivity and cost-efficiency.
Coordination and governance of industrial symbiosis relationships among biomass suppliers, technology providers and off-takers.
Commercialisation and market development activities.
Development of long-term feedstock supply agreements.
Sustainability assessment activities including Life Cycle Assessment (LCA), techno-economic assessment and carbon footprint evaluation.

5) Key Resources

Continuous access to Corn Steep Liquor generated by the regional starch industry.
Existing industrial biotechnology infrastructure available in Flanders.
Fermentation and downstream processing technologies for 1,3-PDO production.
Pilot and demonstration facilities such as Bio Base Europe Pilot Plant.
Highly skilled workforce in industrial biotechnology, bioprocess engineering and sustainable chemistry.
Intellectual property related to microbial strains, fermentation processes and purification

2) Value Proposition

Production of renewable and bio-based 1,3-Propanediol from an underutilised industrial side-stream.
Valorisation of Corn Steep Liquor, transforming an industrial by-product into a high-value platform chemical.
Reduction of waste generation and improvement of resource efficiency through industrial symbiosis.
Reduced dependence on fossil-based chemical feedstocks.
Lower greenhouse gas emissions compared to conventional petrochemical production routes.
Contribution to circular economy objectives and regional bioeconomy strategies.
Supply of sustainable and traceable bio-based chemicals for multiple industrial sectors.
Increased competitiveness and sustainability performance for participating industries.
Creation of new revenue streams for agro-industrial companies generating CSL.
Strengthening regional strategic autonomy through local resource valorisation.
Enhancement of regional resilience by reducing dependency on imported fossil-based intermediates.
Support to corporate sustainability reporting and ESG objectives.

4) Customer Relationships

Long-term B2B supply agreements with industrial customers.
Strategic partnerships with polymer and chemical manufacturers.
Joint innovation and co-development projects with downstream users.
Technical assistance and customised product development.
Sustainability reporting and traceability services.
Participation in cluster activities, industrial networking events and demonstration projects.
Collaborative innovation partnerships throughout the value chain.

3) Channels

Direct B2B sales to chemical and polymer manufacturers.
Industrial symbiosis platforms and cluster networks.
Bioeconomy brokerage events and trade fairs.
Regional innovation ecosystems and demonstration activities.
Strategic partnerships with specialty chemical distributors.
Digital industrial platforms supporting circular value chains.
Collaborative projects and pilot

1) Service Model

Integrated B2B service combining bio-based 1,3-PDO supply, technical support and circularity documentation.
Feedstock-supply coordination service connecting CSL producers, logistics operators and fermentation partners.
Sample-to-scale supply model, allowing customers to test bio-based 1,3-PDO at pilot scale before moving to long-term industrial supply.
Co-development services with polymer, textile, cosmetics and chemical companies to adapt 1,3-PDO specifications to end-use requirements.
Sustainability documentation package, including traceability, circularity metrics, MFA-based reporting, LCA inputs and ESG-support information.
Industrial symbiosis brokerage service, facilitating long-term agreements between biomass suppliers, technology providers and off-takers.
Technical assistance for downstream customers using 1,3-PDO in PTT, resins, coatings, solvents, personal care ingredients and other applications.
Support for certification and compliance with bio-based, low-carbon and circular economy claims.
Customer onboarding through pilots, demonstration activities and cluster-based matchmaking in the Flemish ecosystem.

8) Cost Model

Feedstock collection, storage and transportation costs.
Pre-treatment and biomass conditioning costs.
Fermentation operating costs (utilities, nutrients, energy and consumables).
Downstream purification and separation costs.
Capital expenditures for biorefinery infrastructure and equipment.
Labour and specialised personnel costs.
Research, development and process optimisation activities.
Quality assurance, certification and regulatory compliance costs.
Logistics and product distribution costs.
Costs associated with coordination and governance among industrial partners.
Sustainability monitoring, reporting and certification costs.
Costs related to establishing long-term feedstock agreements and industrial symbiosis contracts.

9) Revenue Model

Sales of bio-based 1,3-Propanediol.
Premium pricing associated with renewable and low-carbon products.
Revenues from long-term supply contracts with industrial customers.
Licensing of fermentation technologies and process know-how.
Revenues generated through industrial symbiosis arrangements.
Valorisation of additional co-products and side-streams.
Public funding and innovation support schemes during scale-up phases.
Potential revenues linked to carbon reduction incentives and sustainability-related mechanisms.

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Corn Steep Liquor (CSL) → 1,3-Propanediol (1,3-PDO) for Brussels (Belgium)

7) Key Partners

Corn wet milling and starch processing industries located in neighbouring regions (primarily Flanders and Wallonia).
Industrial biotechnology companies specialised in fermentation and downstream processing.
Universities and research organisations (ULB, VUB, UCLouvain Brussels campus, VITO Brussels office).
Innovation clusters and circular economy organisations (e.g., GreenWin, Cluster Tweed, regional innovation hubs).
Industrial symbiosis facilitators and circular economy platforms.
Logistics providers specialised in biomass transport and storage.
Bio Base Europe Pilot Plant and other external pilot-scale facilities.
Regional public authorities and funding agencies supporting circular economy initiatives.
Technology providers, equipment suppliers and engineering companies.
Chemical and polymer manufacturers acting as industrial off-takers.

6) Product System

Coordination of biomass sourcing from neighbouring regions.
Development and management of industrial symbiosis partnerships.
Innovation, demonstration and pilot activities for 1,3-PDO applications.
Business development and commercialisation activities.
Technology transfer and knowledge exchange.
Sustainability assessment, LCA, techno-economic assessment and ESG reporting.
Circularity monitoring through Material Flow Analysis.
Stakeholder engagement and ecosystem development.
Regulatory support, certification and standardisation activities.
Market development and customer relationship management.

5) Key Resources

Strong regional innovation ecosystem.
Highly skilled workforce in biotechnology, sustainability and circular economy.
Research and innovation infrastructure.
Knowledge and expertise in industrial symbiosis and circular business models.
Access to Belgian and European funding programmes.
Extensive stakeholder and cluster networks.
Intellectual property related to fermentation technologies and process optimisation.
Digital platforms and sustainability monitoring systems.

2) Value Proposition

Production and supply of renewable and bio-based 1,3-Propanediol through a circular industrial symbiosis approach.
Valorisation of Corn Steep Liquor generated in neighbouring regions.
Creation of cross-regional industrial symbiosis networks within Belgium.
Reduction of fossil resource dependence and greenhouse gas emissions.
Provision of sustainable, traceable and low-carbon chemical intermediates.
Strengthening of the Brussels circular economy ecosystem.
Support for corporate sustainability, ESG and reporting objectives.
Increased regional innovation capacity and knowledge transfer.
Facilitation of market uptake of bio-based chemicals through demonstration and innovation services.
Enhancement of regional resilience through diversified and circular supply chains.

4) Customer Relationships

Long-term strategic partnerships with industrial customers.
Collaborative innovation and co-development projects.
Technical support and consulting services.
Sustainability and circularity reporting support.
Participation in innovation networks, clusters and demonstration activities.
Continuous stakeholder engagement and knowledge exchange.

3) Channels

Direct B2B sales.
Innovation and cluster networks.
Circular economy and bioeconomy platforms.
Demonstration projects and pilot activities.
Brokerage events and trade fairs.
European and regional innovation programmes.
Digital collaboration and matchmaking platforms.

1) Service Model

Integrated B2B service combining bio-based 1,3-PDO supply, innovation support and sustainability services.
Industrial symbiosis brokerage service connecting CSL suppliers, technology providers and industrial users across Belgium.
Innovation and demonstration services supporting pilot testing and market uptake of bio-based 1,3-PDO.
Sustainability and circularity advisory services, including LCA, MFA and ESG reporting support.
Co-development services with downstream industries to tailor bio-based products to customer requirements.
Matchmaking and networking services facilitated through clusters and innovation ecosystems.
Technical support and certification assistance for bio-based and circular products.

8) Cost Model

Biomass sourcing and transportation costs.
Logistics and storage costs.
Fermentation and downstream processing costs.
R&D, pilot testing and demonstration activities.
Personnel and specialised expertise costs.
Partnership coordination and governance costs.
Sustainability assessment and reporting costs.
Certification and regulatory compliance costs.
Business development and stakeholder engagement costs.
Innovation ecosystem participation costs.

9) Revenue Model

Sales of bio-based 1,3-Propanediol.
Premium pricing for renewable and low-carbon products.
Revenues from innovation and technical support services.
Consultancy services related to circularity and sustainability.
Technology licensing and knowledge transfer revenues.
Public funding and innovation grants.
Revenues derived from industrial symbiosis agreements.
Demonstration and collaborative project funding.

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Corn residues → Succinic acid

7) Key Partners

•Corn residue suppliers and aggregators in Piedmont: maize growers, agricultural cooperatives, corn-handling companies and feed/starch processors able to mobilise corn stover and straw as secondary biomass.
•Specific potential feedstock actors identified in SYMBIO: Sedamyl S.p.A. , Sacchetto S.p.A. , Dalma Mangimi S.p.A. and Ferrero Mangimi S.p.A. as corn-handling/feed-sector companies linked to the BioLink.
•Technology and conversion partners: Roquette Italia , identified as having direct experience in bio-succinic acid , plus potential complementary partners such as Novamont and ENI Versalis if scale-up or additional technologies are considered.
•Regional agro-industrial processors and chemical-sector actors supporting aggregation, processing and downstream integration of corn residues into a higher-value biochemical pathway.
•Logistics and storage operators able to manage bulky, low-density and seasonal agricultural residues, with residue-removal decisions constrained by soil-health and erosion considerations .
•Research, pilot and industrial biotechnology partners for enzymatic hydrolysis, microbial fermentation, inhibitor management and downstream processing optimisation .
•Industrial off-takers from bioplastics, PBS, BDO/polyester polyols, resins, coatings, polyurethanes, solvents, specialty chemicals and pharmaceutical-intermediate value chains.
•Industrial symbiosis facilitators, regional clusters, public authorities and SYMBIO/VCG.AI ecosystem

6) Product System

•Core product: bio-based succinic acid , a versatile C4 dicarboxylic platform chemical with applications in biodegradable plastics such as PBS, specialty resins, polyurethanes, solvents, coatings, pharmaceuticals, food applications and personal-care/cosmetic value chain.
•Feedstock: corn residues, specifically corn stover and straw, generated after the primary maize harvest. The Piedmont MFA assumes approximately 1.25 Mt/year of corn residues entering the biorefinery as theoretical regional potential.
•Conversion process: lignocellulosic pretreatment and enzymatic hydrolysis to release fermentable sugars, followed by microbial fermentation to succinic acid.
•Auxiliary inputs: acids for pretreatment, enzymes and fermentation nutrients. The MFA scenario includes 36,464 t acid, 10,024 t enzymes and 91,472 t nutrients.
•Main output: approximately 390 kt/year of

5) Key Resources

•Regional biomass base: approximately 1.25 Mt/year corn residues considered in the Piedmont MFA scenario, derived from corn stover and straw availability assumptions .
•Agricultural and agro-industrial supply base: maize production, corn-handling companies, feed-sector actors and starch-processing capacities identified in the Piedmont BioLink .
•Biorefinery process assets: pretreatment, enzymatic hydrolysis, fermentation, downstream separation/purification, wastewater treatment and utilities .

2) Value Proposition

•Valorisation of a major regional agricultural residue into a higher-value bio-based platform chemical, shifting corn stover and straw away from lower-value or competing uses where sustainable residue availability allows it .
•Bio-based alternative to fossil-derived succinic acid, supporting the substitution of petrochemical intermediates in polymers, coatings, resins and specialty chemical applications .
•Large theoretical production potential: the Piedmont MFA estimates around 390 kt/year bio-SA from approximately 1.25 Mt/year corn residues under harmonised SYMBIO assumptions .
•Industrial-symbiosis narrative: connects agricultural residue producers, fermentation/biorefinery actors and downstream chemical or bioplastic users within a regional circular bio-based value chain .
•Climate and circularity benefits: fermentation can bind CO_2 during the production cycle, while lignin-rich residues may be used internally for steam and electricity, reducing external fossil-energy demand .
•Regional competitiveness: leverages Piedmont's corn-starch/feed base, agro-industrial processors, chemical actors and existing bio-based innovation experience .
•Market relevance: succinic acid has recognised applications in bioplastics/PBS, BDO, polyester polyols, coatings, pharmaceuticals, food applications, surfactants, detergents, flavours, fragrances and biodegradable polymers .

4) Customer Relationships

•Long-term B2B off-take agreements with bioplastics, polymer, resin, coating and specialty-chemical customers requiring reliable bio-SA supply.
•Strategic co-development relationships with downstream users where succinic acid purity, formulation performance and application-specific qualification are decisive .
•Collaborative, multi-actor relationships with maize growers, aggregators and processors to secure predictable residue volumes while respecting soil-health constraints and competing uses .
•Tiered engagement model: sample/pilot quantities for technical validation, followed by larger industrial supply agreements once quality, yield and logistics are validated.
•Technical support for customers using bio-SA in PBS, polyurethanes, resins, coatings, solvents and specialty materials .

3) Channels

•Direct B2B sales to bioplastic, PBS, polymer, BDO/polyester polyol, resin, coating, polyurethane, solvent and specialty-chemical manufacturers .
•Strategic partnerships with regional and national bio-based chemical producers, fermentation actors and downstream industrial users .
•SYMBIO/VCG.AI and industrial symbiosis platforms to identify and connect feedstock suppliers, technology providers and off-takers .

1) Service Model

•Integrated B2B service combining bio-based succinic acid supply, technical support and circularity documentation.
•Feedstock-supply coordination service connecting maize producers, corn processors, logistics operators and fermentation/biorefinery partners in a regional industrial-symbiosis model .
•Residue-allocation advisory support to define how much corn stover/straw can be mobilised without compromising soil organic matter, erosion control or existing feed/bioenergy uses .
•Sample-to-scale supply model, allowing industrial customers to validate bio-SA quality and application performance before entering long-term supply agreements.
•Co-development services with polymer, resin, coating and specialty-chemical users to adapt bio-SA specifications to downstream requirements .
•Sustainability documentation package including traceability, circularity metrics, MFA-based reporting, LCA input data and ESG-support information .
•Industrial symbiosis brokerage service facilitating long-term agreements between residue suppliers, technology providers, off-takers and by-product users.
•By-product valorisation service, identifying outlets for formic acid, acetic acid, lignin-rich residues and non-fermented sugars .

8) Cost Model

•Feedstock mobilisation costs: collection, baling/handling, storage and transport of low-density, spatially dispersed corn residues .
•Residue-supply premium and opportunity cost: corn stover/straw already competes with livestock feed, bioenergy/biogas and soil-retention requirements, limiting the realistically accessible volume .
•Capital expenditure: pretreatment equipment, enzymatic hydrolysis units, fermentation capacity, downstream processing, wastewater treatment, utilities and storage infrastructure .
•Operating costs: acids, enzymes, nutrients, utilities, energy, process water, labour, maintenance and quality assurance. Main MFA input categories include acid, enzymes and nutrients .
•Downstream processing cost: purification and recovery are the dominant economic bottleneck and can exceed 50% of total production expenses for fermentation-derived succinic acid .
•Technology-validation costs: regional empirical validation is needed because experts scrutinised yield expectations and highlighted inhibitory effects of unwashed hydrolysates .

9) Revenue Model

•Primary revenue: sale of bio-based succinic acid to bioplastics/PBS, resin, coating, polyurethane, solvent, specialty-chemical and pharmaceutical-intermediate customers .
•Premium pricing in sustainability-driven applications where customers value bio-based origin, traceability, lower fossil dependence and circular feedstock use .
•Long-term industrial supply contracts with downstream users seeking renewable platform chemicals and stable sourcing.
•By-product revenue potential from formic acid and acetic acid, depending on purity, separation costs and local offtake agreements .
•Avoided-cost or internal-value stream from lignin-rich residues used for on-site steam/electricity generation, reducing external energy demand .
•Additional upside from non-fermented sugars if process optimisation enables further conversion to succinic acid or other products .
•Service-based revenue from sample provision, application testing, sustainability documentation and co-development support

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Whey to Proteins (Italy)

7) Key Partners

Cooperative base: numerous Latteria Sociale cooperatives producing Montasio DOP and other latteria cheeses .

Innovation/coordination partner: Agrifood FVG, running the Dairy+ project .

Academic partners: University of Udine (Department of Agri-food, Environmental and Animal Sciences) and, cross-border, the University of Ljubljana's Institute for Dairy Science and Probiotics .

Regional government partner: Regione Autonoma Friuli Venezia Giulia, via PSR dairy-sector capital grants and DOP/IGP documentation support .

Cross-border EU funding partner: the Interreg VI-A Italia–Slovenia programme, which co-finances Dairy+ , a funding relationship with no direct Walloon equivalent identified in this research.

6) Product System

Dairy+'s demonstrated product line is specific and food-facing: high-protein cheese and probiotic yogurt made using recovered whey protein, explicitly targeted at sports-nutrition and vegetarian-diet consumer segments , a narrower, more applied product concept than "WPC/WPI as a bulk ingredient," but closer to market-ready for small/medium caseifici.

Co-products (lactose, minerals, permeate) would still need a separate offtake route (feed, food-grade lactose, or anaerobic digestion) , which Dairy+'s public materials do not appear to address directly.

Full industrial-grade WPC/WPI/hydrolysate production, and any infant-formula-grade fraction under EU compositional rules , would require aggregating volume beyond what individual FVG cooperatives can supply alone.

5) Key Resources

Feedstock: fragmented across many small Latteria Sociale cooperatives (the "turnaria" model dating to 1881) producing Montasio DOP and other latteria cheeses in comparatively small batches per site — individually below the volume threshold that would justify a dedicated UF/NF line at any single dairy.

Regional academic and institutional resource: the University of Udine's Department of Agri-food, Environmental and Animal Sciences is an active, in-region research partner already engaged in whey valorisation work through

2) Value Proposition

Confirmed local pain point: the region's dairy sector is structured around many small Latteria Sociale cooperatives producing Montasio DOP and other latteria cheeses , each individually generating whey volumes too small to justify their own protein-extraction line, a fragmentation problem rather than a single-site disposal problem.

The Dairy+ project's own framing is explicitly market-facing rather than purely environmental: it targets the fast-growing sports-nutrition and vegetarian/high-protein segments as the commercial hook for getting small/medium caseifici to adopt circular whey recovery .

Same EU-level regulatory alignment applies (Farm to Fork, infant-formula compositional rules for whey fractions under Delegated Regulation (EU) 2016/127) .

4) Customer Relationships

Dairy+ is itself a structured, multi-year relationship between Agrifood FVG, the University of Udine and the University of Ljubljana, explicitly designed to be extended to "small and medium caseifici" across the region as a demonstration/knowledge-transfer relationship rather than a commercial supply contract .

Because FVG's dairy base is dominated by small Latteria Sociale cooperatives, any commercial-scale customer relationship (e.g., with a sports-nutrition brand) would most plausibly need to be brokered collectively (via Agrifood FVG or a similar consortium) rather than negotiated by a single small caseificio .

Regional PSR funding support for the dairy sector gives cooperatives a way to co-invest in the shared infrastructure a collective

3) Channels

Direct-to-regional-consumer channels already exist through platforms like "IoFVG", which distributes FVG-origin dairy products regionally with plans to expand nationally/internationally , a channel template that could extend to a whey-protein-enriched product line if Dairy+'s cheese/yogurt outputs are commercialised.

Cross-border channel potential via the Interreg Italia–Slovenia structure underpinning Dairy+, which explicitly targets FVG, Veneto and Slovenian markets

1) Service Model

Agrifood FVG (the regional agri-food innovation body) is running "Dairy+", an EU Interreg VI-A Italia–Slovenia co-funded project that converts whey into high-protein cheese and probiotic yogurt, explicitly designed to demonstrate circular whey recovery to small and medium dairies across FVG, Veneto and Slovenia .

Dairy+ pairs Agrifood FVG with the University of Udine's Department of Agri-food, Environmental and Animal Sciences and the University of Ljubljana's Institute for Dairy Science and Probiotics, an active applied-research service layer that a Friulian dairy can plug into, rather than needing to build alone .

FVG's regional rural-development programme (PSR) includes capital grants and subsidised financing specifically to address structural weaknesses in the dairy sector , giving smaller cooperatives a funding route to co-invest in shared service infrastructure.

8) Cost Model

Regional PSR funding provides capital grants and subsidised financing explicitly earmarked for addressing dairy-sector structural weaknesses , and the Dairy+ project itself is EU Interreg co-funded , meaningfully lowering the effective capex/opex burden for a demonstration-scale project in FVG compared with an equivalent Walloon project that would currently need to find its own funding route.

Aggregation/logistics cost: coordinating whey collection across many small Latteria Sociale sites (rather than one large plant) implies higher per-tonne logistics cost than Wallonia's more concentrated feedstock base, even before considering processing capex .

9) Revenue Model

Near-term realistic revenue: premium-positioned, branded food products (high-protein cheese, probiotic yogurt) sold into sports-nutrition and vegetarian-diet consumer segments, following the Dairy+ demonstration model , a differentiated-product revenue strategy rather than a bulk-ingredient one.

Regional distribution revenue channel: platforms such as IoFVG already distribute FVG-origin dairy products regionally, with stated plans to expand nationally and internationally , offering a plausible go-to-market route for a Dairy+-derived product line.

Co-funded de-risking: because Dairy+ itself is EU Interreg-funded and PSR capital grants are available regionally , the revenue case for FVG cooperatives does not need to cover full capex recovery from day one, unlike a fully commercial Walloon project.

Bulk WPC/WPI/hydrolysate revenue (the global price range in) remains a longer-term, aggregation-dependent opportunity

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Whey to Proteins (Belgium)

7) Key Partners

Dairy cooperative: Solarec / Laiterie des Ardennes .

Cluster/innovation partner: Wagralim, the Walloon competitive food cluster, coordinating circular-economy and co-product valorisation initiatives regionally .

Academic partner: University of Liège – Gembloux Agro-Bio Tech .

Missing/gap: no confirmed in-region specialty-ingredient partner equivalent to Arla Foods Ingredients' role for Milcobel ; this is the clearest partnership gap in the Walloon case and the single most important one to close for a Walloon whey-protein strategy to work.

6) Product System

Realistic near-term product: standard-grade WPC (34–80%) from Solarec's mozzarella-whey stream, if a food-grade offtake partnership were established (following, but not yet replicating, the Flemish Milcobel model) .

Currently, actual regional product system is skewed toward animal feed and land application of whey rather than any protein fraction , the "product system" as it exists today in Wallonia is closer to a feed/agronomic co-product stream than a food-ingredient one.

Full global product range (WPI 90%+, hydrolysates, infant-formula-grade fractions under Delegated Regulation (EU) 2016/127) remains aspirational for the region absent a new capital investment and partnership.

5) Key Resources

Feedstock: Solarec/Laiterie des Ardennes, based in the Belgian Ardennes, processes roughly 1.25–1.55 billion litres of milk/year and has added a growing mozzarella line (~32,000–40,000 tonnes/year), which is the kind of co-product stream (mozzarella whey) that supported the Flemish Milcobel–Arla partnership .

Important gap: the best-documented Belgian whey-to-protein case (Milcobel, Langemark) is in West Flanders, not Wallonia — Wallonia's own confirmed position, per Wagralim's technical experts, is that whey is mostly still directed to pig feed and land-spreading rather than food-grade extraction .

Regional academic resource: University of Liège – Gembloux Agro-Bio Tech, based in Gembloux (Wallonia), hosts agro-food quality and food-

2) Value Proposition

Confirmed local pain point: whey management becomes "constraining" for Walloon cheese/dairy plants once volumes are significant, and transport-of-whey regulations complicate direct sale to livestock farmers , a genuine, source-confirmed disposal problem that supports the valorisation case.

Forward-looking scarcity argument: a cited dairy-technology expert projects that by 2030 there will not be enough lactose globally to meet demand, driven partly by infant-formula-powder growth requiring whey-derived lactose and soluble proteins , this reframes whey/lactose less as waste and more as an emerging supply-constrained ingredient, which is a stronger commercial argument than a pure circularity pitch.

Regulatory alignment: EU Farm to Fork's 50% food-waste-reduction ambition , echoed by Wallonia's own "Circular Wallonia" regional strategy under which Wagralim operates .

4) Customer Relationships

No confirmed Walloon co-development relationship at the Milcobel–Arla level exists in this research; the nearest useful template is that Flemish partnership, which a Walloon plant (most plausibly Solarec) could seek to replicate with a specialty-ingredient partner .

Wagralim-mediated relationships are consultative/brokerage in nature at this stage (helping producers find buyers or process partners for co-products) rather than long-term supply contracts .

Upstream relationship: Solarec's cooperative structure (part of Laiterie des Ardennes) means governance and investment decisions run through farmer-shareholders, which can slow (but also de-risk, via shared ownership) a move into new capex-heavy protein-extraction lines .

3) Channels

Direct B2B is realistic mainly for Solarec at its current scale (1.25–1.55 billion litres of milk/year, including a growing mozzarella line) , but there is no confirmed Walloon example of a food-grade whey-protein ingredient sale at the scale of Milcobel's Flemish partnership with Arla .

Wagralim functions as a channel-building intermediary, connecting Walloon agri-food producers with potential co-product buyers and partners , which is the more realistic near-term channel for a smaller Walloon dairy than direct trade-fair presence.

Trade fairs (Fi Europe, Vitafoods Europe) remain accessible in principle , but require a marketing/technical-sales investment that fits a Solarec-scale player more than a small cooperative

1) Service Model

Wagralim, the Walloon competitive food cluster, coordinates the agri-food side-stream valorisation agenda under the regional "Circular Wallonia" strategy, with a dedicated project manager for circular-economy coordination across the agri-food value chain .

Wagralim's own technical content acknowledges that whey remains genuinely difficult to valorise toward human consumption in Wallonia today, most Walloon whey is currently routed to pig feed or land-spreading rather than food-grade protein extraction , which is an important, source-confirmed correction to any assumption that a mature whey-protein service layer already exists regionally.

Realistic near-term service offer: co-product routing advisory (feed vs. spreading vs. eventual protein extraction) and cluster-brokered introductions to processing partners, rather than an established in-house formulation-support service .

8) Cost Model

A confirmed additional cost/constraint: regulatory requirements around whey transport complicate direct sale to livestock farmers , meaning even the current (lower-value) feed-oriented whey economy carries a compliance cost that a shift toward food-grade valorisation would need to solve differently, not avoid.

No confirmed dedicated regional co-funding instrument for whey-specific capex was identified (Wallonia's Circular Wallonia strategy, as administered through Wagralim, appears more developed for pea protein than for whey) , this is a cost-model gap: a Walloon whey project may need to self-fund capex or seek EU-level (rather than regional) funding.

9) Revenue Model

Near-term realistic revenue: continued sale of raw/lightly processed whey into animal feed and land-application markets, a low-value, currently dominant revenue line per Wagralim's own account .

Medium-term opportunity (contingent on a new partnership): WPC/WPI ingredient sales at the price levels seen regionally (~€1,700/tonne standard whey powder to ~€20,000/tonne for ≥90% protein concentrate in 2026) , but this requires the missing ingredient-partner relationship flagged in Key Partners.

Long-term structural tailwind: the lactose-scarcity argument advanced by dairy-technology experts (insufficient global lactose supply by 2030) suggests that even Wallonia's currently low-value lactose/whey stream could see rising prices independent of any new protein-extraction investment, a revenue upside that does not require Wallonia to solve the protein-extraction problem first.

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Forestry residues to PHA (Andalusia)

7) Key Partners

Versalis / Eni (Crescentino, Rivalta Scrivia, Novara) — the central industrial partner for any wheat-straw-to-PHA strategy in Italy .
Novamont (Novara, Terni, Porto Torres, Bottrighe, Piana di Monte Verna) — an adjacent bioplastics partner with market access, though not currently working with straw-derived sugars .
EU-project partners via ELLIPSE (PHA from slaughterhouse waste and paper/pulp sludge, with Novamont) — a template co-development consortium, though on different feedstocks .
Agricultural supply base: farmer networks in Piedmont (Crescentino's existing supply area) and, per the Apulian study, in Puglia .
Originally, Novozymes co-developed the Crescentino plant's enzymatic hydrolysis step alongside Beta Renewables (now part of Versalis) — a useful historical technology partner reference, though current ownership sits entirely with Versalis/Eni following the 2018 acquisition
Versalis/Eni ; Novamont ; ELLIPSE consortium ; Piedmont/Puglia farmer supply base .

6) Product System

Currently commercial product at Crescentino: second-generation bioethanol (ISCC-EU certified, ~25,000 tonnes/year capacity from ~200,000 tonnes/year of biomass), used to formulate gasoline with a renewable component, plus a bio-based hand/surface disinfectant product (Invix®) using the site's ethanol .
Near-term R&D product, not yet commercial: PHA and other biopolymers from the same PROESA-derived second-generation sugars, explicitly named as a Versalis Biotech research target — the direct wheat-straw-to-PHA link exists at R&D stage but has not been confirmed as commercially operating in this research.
Adjacent, already-commercial Italian bio-based products: Novamont's Mater-Bi (starch/vegetable-oil bioplastics) and MATER-BIOTECH's bio-based 1,4-butanediol — different feedstock, but proof that Italy already commercialises bio-based polymer products at scale.
Lignin co-product used for on-site energy rather

5) Key Resources

The Crescentino biorefinery (Vercelli, Piedmont), owned by Versalis (Eni), is built entirely around PROESA® technology and is designed to process up to roughly 200,000–270,000 tonnes/year of lignocellulosic biomass, including wheat straw, rice straw and giant reed (Arundo donax) — a real, operating, industrial-scale pretreatment/hydrolysis asset that converts straw into fermentable second-generation sugars.
Feedstock base: ~10 million tonnes/year of straw residue nationally, concentrated in Veneto, Puglia, Friuli, Lombardia and Emilia-Romagna ;
a farmer willingness to supply study in Apulia

2) Value Proposition

Genuine surplus: Italy generates around 10 million tonnes of straw residue per year, part of an estimated 14.5–15 million tonnes/year of total unused agricultural residues nationally , concentrated in Veneto, Puglia, Friuli, Lombardia and Emilia-Romagna (residue surface concentration of 105–155 t/km²) .
Explicit non-food-competing framing: Versalis's PROESA technology at Crescentino was designed from the outset to process "agricultural by-products, woody material or plants not suitable for food consumption," including straw — a genuinely strong circularity/non-food-competition argument, stronger than most first-generation biomass feedstocks.
Straw is frequently burned post-harvest in the absence of a valorisation route, a recognised source of air pollution flagged directly in the wheat-straw PHA research literature — a real disposal/environmental pain point, distinct in kind from whey's BOD/wastewater problem but functionally similar as a "genuine local problem" argument.
Regulatory tailwind: the EU accounted for roughly 47% of the global PHA market by value in 2025 on one estimate, attributed to strict biodegradable-plastics regulation and circular-economy policy ; the EU Single-Use Plastics Directive is estimated to have removed about 3.4 million tonnes of conventional plastic items from EU markets between 2021 and 2024 .
~10 Mt/yr straw residue, non-food-competing PROESA framing, post-harvest burning as a real disposal problem

4) Customer Relationships

Versalis/Eni's relationship model with its industrial chemical customers (via its existing distribution and account-management structure) is the plausible template for a future PHA customer relationship, once PHA moves from the Rivalta Scrivia/Novara R&D stage to commercial supply .
Novamont's ELLIPSE project shows an active co-development relationship model already being used for PHA (from other feedstocks), which is directly transferable in structure, if not in substrate, to a wheat-straw PHA programme .
Upstream relationship: Crescentino's original design already incorporates a farmer/agricultural-supply relationship for biomass collection in the Piedmont/northern Italy area, with documented straw-supply cost benchmarks from a comparable Apulian farmer study (€21–23/tonne) .

3) Channels

Versalis/Eni's existing chemicals distribution network and industrial B2B relationships are, in principle, a channel a commercialised straw-PHA product could use — though Crescentino's current commercial output is bioethanol (ISCC-EU certified, blended into gasoline), not PHA, so this channel is not yet activated for PHA specifically .
Novamont's Mater-Bi channels — carrier bags, agricultural mulch film, food packaging, catering/tableware, waste-collection bags — represent an established Italian bioplastics market access route that a

1) Service Model

Versalis (Eni's chemical company) operates dedicated Biotech Research Centres at Rivalta Scrivia (Alessandria) and Novara that are explicitly developing PHA and other biopolymer intermediates from second-generation sugars produced with its proprietary PROESA® pretreatment technology — a genuine in-house technical-service capability that most PHA start-ups elsewhere do not have access to.
Novamont's "third-generation biorefinery" model, spanning production sites in Novara, Terni, Porto Torres, Bottrighe and Piana di Monte Verna, already provides application/technical support to industrial customers for its Mater-Bi bioplastic range, giving Italy an established bioplastics customer-service infrastructure, even though it is currently starch/vegetable-oil based rather than straw-PHA .
Novamont is a partner in the EU-funded ELLIPSE project, which is developing cost-efficient PHA production from slaughterhouse waste and paper/pulp sludge (co-processed with dairy sludge and glycerol) — demonstrating an active PHA co-development service model in Italy, albeit on different feedstocks than wheat straw.
Gap flagged: none of this technical-service capacity is currently packaged specifically around wheat straw as a PHA feedstock; it would need to be extended from adjacent,

8) Cost Model

Crescentino's original 2013 capex was approximately €150 million for the ethanol plant alone , and the site subsequently required a multi-year, multi-investment restart process after being idled — plants were confirmed "up and running" only by 2020, with actual bioethanol production onstream from February 2022, roughly nine years after the original 2013 opening — a real, sobering illustration that even a technologically proven, well-capitalised straw-biorefinery can face years of commercial-viability difficulty.
Feedstock collection cost is quantified at €21–23/tonne of wheat straw in the comparable Apulian case .
Because Crescentino already exists, the incremental cost of adding a PHA production line (fermentation, downstream extraction) is materially lower than the cost of building a new straw-to-sugars pretreatment facility from scratch — an important, Italy-specific cost advantage.
Crescentino's original ~€150M capex and ~9-year path to full commercial operation (2013–2022) as a cautionary benchmark ; incremental PHA-line addition cheaper than a new-build

9) Revenue Model

Live, near-term revenue: bioethanol sales from Crescentino (ISCC-EU certified, blended into gasoline), at a maximum production capacity of approximately 25,000 tonnes/year from around 200,000 tonnes/year of biomass input — a real, operating revenue line, though not a PHA revenue line.
Medium-term PHA revenue: contingent on Versalis's Rivalta Scrivia/Novara R&D reaching commercial scale, into a global PHA market whose 2026 value is estimated anywhere between roughly $64 million and $153 million depending on the source (a notably wide spread, flagged explicitly rather than resolved) , growing at a reported CAGR ranging from about 8% to 29% depending on the analyst .
Adjacent, already-realised revenue: Novamont's Mater-Bi and MATER-BIOTECH bio-BDO lines demonstrate that Italy already converts bio-based polymer R&D into commercial revenue, which is a relevant proof point even though it is not the straw-PHA product itself .
Live bioethanol revenue (~25,000 t/yr capacity) ; medium-term PHA revenue contingent on Versalis R&D, into a global PHA market estimated at $64M–$153M in 2026 depending on source (wide divergence flagged) ; adjacent proven revenue via

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Forestry residues to PHA (Croatia)

7) Key Partners

National Institute of Chemistry (Kemijski inštitut), including researchers active in biorefining such as Dr. Blaž Likozar .
University of Ljubljana, Faculty of Chemistry and Chemical Technology (FKKT) .
National research consortium behind BRIDGE2BIO (2018–2021) and BIOEASTsUP (2019–2022), described as bringing together "leading national applied life science research institutions" .
Interreg Central Europe (TeBiCE project) as a cross-border EU-funding partner, though not yet applied to straw/PHA specifically .
Missing/gap: no confirmed Slovenian industrial partner equivalent to Versalis exists in this research; this is the single largest partnership gap in the Slovenian case.
National Institute of Chemistry ; Univ. of Ljubljana FKKT ; BRIDGE2BIO/BIOEASTsUP consortium ; TeBiCE/Interreg Central Europe

6) Product System

No confirmed commercial product; the most advanced documented output is lab-scale P(3HB) (poly-3-hydroxybutyrate, a PHA subtype) produced via fermentation of a lignocellulosic hydrolysate at University of Ljubljana, though from paper-industry residue rather than wheat straw specifically .
Any commercial-scale product system would need to be built essentially from zero, most plausibly by adapting Italian (PROESA) or other proven European pretreatment technology rather than developing a novel domestic process.
lab-scale P(3HB) from lignocellulosic hydrolysate only (paper-industry substrate, not straw)

5) Key Resources

No confirmed industrial-scale lignocellulosic pretreatment facility exists in Slovenia; the country's own bioeconomy strategy papers state explicitly that biorefinery capacity is absent nationally .
Academic resources: National Institute of Chemistry (biorefining research group) and University of Ljubljana FKKT (PHA-from-lignocellulosic-hydrolysate fermentation research) are real, but lab-scale.
Feedstock base: national wheat/spelt output of roughly 140,000–158,000 tonnes/year , an order of magnitude smaller than Italy's straw-residue pool, and fragmented across small farms (average 5.6–6.9 ha) .
Slovenia's chemical industry is separately noted as "one of the most competitive industries" nationally, and the country is described as "abundant with lignocellulosic biomass," which the national bioeconomy dossier frames as an

2) Value Proposition

Much smaller absolute surplus: Slovenian wheat and spelt output has run at roughly 140,000–158,000 tonnes/year in recent years , an order of magnitude below Italy's straw-residue base, so any Slovenian value proposition needs to be built around a smaller, more geographically concentrated feedstock pool rather than a large industrial surplus.
Structural fragmentation is the more relevant "problem" in Slovenia's case: the average Slovenian farm is roughly 5.6–6.9 hectares, with 60% of holdings under 5 hectares — a similar small-farm fragmentation pattern to the one already identified in the FVG dairy case, but here on the arable/cereal-farming side rather than the dairy-processing side.
Slovenia's own bioeconomy strategy papers explicitly identify "unused potential of residues and by-products in production, processing and consumption" as a national gap, alongside "the absence of biorefinery capacities" — meaning the valorisation case is nationally recognised as an opportunity, not yet realised.
Same EU-level regulatory tailwind applies equally (EU PHA market share, Single-Use Plastics Directive) .

much smaller feedstock base (~140–158 kt/yr wheat), fragmented small-farm structure, nationally acknowledged valorisation gap

4) Customer Relationships

Relationships currently sit almost entirely within research consortia — BRIDGE2BIO, BIOEASTsUP, and Interreg-funded projects like TeBiCE bring together national applied life-science institutions rather than commercial supply-chain partners .
No confirmed farmer-to-processor commercial relationship for straw-as-PHA-feedstock was identified; given the small-farm structure (average 5.6–6.9 ha, 60% under 5 ha) , any future commercial relationship would most plausibly need to be brokered collectively, similar to the FVG dairy-cooperative pattern in the earlier canvas.

3) Channels

No confirmed domestic commercial bioplastics-distribution channel was identified in this research; Slovenia's most concrete channel exposure is through EU-level cross-border research/innovation programmes such as Interreg Central Europe's TeBiCE project (Territorial Biorefineries for a Circular Economy), though Slovenia's contribution to that project focused on fruit, oil and wood-processing sectors, not straw or PHA specifically .
Slovenia's small scale (population and agricultural base) means realistic channel access would likely run through export to established Central/Western European bioplastics buyers rather than a domestic market.

1) Service Model

The National Institute of Chemistry (Kemijski inštitut) has an active biorefining research line, with researchers such as Dr. Blaž Likozar presenting on cross-border bio-refining potential for the Eastern European region .
University of Ljubljana's Faculty of Chemistry and Chemical Technology (FKKT) has direct, documented student/research work on optimising PHA fermentation using lignocellulosic hydrolysates (using Bacillus thuringiensis on a paper-industry lignocellulosic hydrolysate, PPMS) — a genuine academic capability adjacent to, but not identical to, wheat-straw PHA.
Slovenia's national bioeconomy strategy work (the BRIDGE2BIO and BIOEASTsUP projects) functions as a de facto advisory/mapping service for potential investors, cataloguing biomass streams and value-chain gaps at a national level .
Gap flagged: Slovenia's own strategic bioeconomy papers state plainly that the country lacks biorefinery capacity and shows low integration between primary producers and processors — meaning any service model in Slovenia today is research-stage, not an operating technical-support function a commercial customer could call on.

National Institute of Chemistry biorefining research ; Univ. of Ljubljana FKKT PHA-fermentation research ; BRIDGE2BIO/BIOEASTsUP national mapping "service"

8) Cost Model

No confirmed biorefinery capex data exists because no comparable facility has been built; any Slovenian project would need to fund the full pretreatment-to-fermentation cost stack from zero, unlike Italy's incremental-addition scenario.
Slovenia's own strategy documents identify the absence of biorefinery capacity as a structural investment gap rather than a quantifiable line item — meaning the real "cost" in Slovenia's case includes the capital and time needed to build a first facility, which Crescentino's own ~9-year timeline suggests should not be underestimated.

9) Revenue Model

No confirmed commercial revenue line exists in this specific value chain; any future revenue would depend on first building or accessing pretreatment/fermentation capacity, most plausibly through EU co-funding (Interreg Central Europe, Interreg Italia-Slovenia, or Horizon Europe-type instruments) given the domestic capacity gap identified in national strategy papers .
Slovenia's revenue case, if built, would likely need to start at a smaller scale than Italy's, consistent with its roughly ten-times-smaller wheat/straw base relative to Italy's national straw-residue pool .



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